THE SUN

"... In them hath he set a tabernacle for the sun,

Which is as a bridegroom coming out of his chamber, and rejoiceth as a strong man to run a race.

His going forth is from the end of the heaven, and his circuit unto the ends of it: and there is nothing hid from the heat thereof."

Psalm xix. 4, 5, 6

THE SUN

ITS PHENOMENA AND PHYSICAL FEATURES

BY

GIORGIO ABETTI

TRANSLATED BY
ALEXANDRE ZIMMERMANN
AND
FRANS BORGHOUTS

WITH
157 ILLUSTRATIONS
IN THE TEXT

LONDON

CROSBY LOCKWOOD & SON LTD

STATIONERS' HALL COURT, E.C.4

1938

First published MCMXXXVIII
By Crosby Lockwood & Son Ltd
Stationers' Hall Court
London, E.C.4

Made and printed in Great Britain

DEDICATED

TO

GEORGE ELLERY HALE

PREFATORY NOTE

Professor Abetti's authoritative work *Il Sole* serves a double purpose. It gives on the one hand a general survey of modern ideas of the physics of the outer layers of the sun, set out in such a way that it may be read with profit by the amateur as well as the professional student of the subject, while on the other hand it gives what is perhaps one of the most complete accounts in existence of the complicated facts concerning the spots and markings on the solar surface and their movements. The book is accordingly well worth translating into English not only for the benefit of English and American readers who want an introduction to the subject, but also for the specialist. There are probably few writers on solar topics who carry in their heads all the facts about the occurrence and motions of spots and markings which Abetti details, and reference to his pages will remind astrophysicists of the existence of a large body of observational material which cries out for investigation by the inductive theorist.

R. v. d. R. WOOLLEY

CONTENTS

ILLUSTRATIONS

PREFACE

TO THE ENGLISH EDITION

A FEW years ago I had the opportunity of writing the chapter "Solar Physics" for volume iv, *Das Sonnensystem*, of the *Handbuch der Astrophysik* issued by Julius Springer, of Berlin. Since that time, in view of repeated requests that a complete but less technical monograph than that suited for the *Handbuch* might be published on our present-day knowledge of the sun, I decided to re-write and enlarge this essay and to prepare a volume in Italian, which was printed by the publisher Hoepli in 1936 and, having been translated, revised, and brought up to date in parts, now appears in its present English form.

The result is this work, which is of a more or less popular nature, as I have not aimed at treating the various subjects exclusively for the benefit of experts, but have endeavoured to set them forth in such a manner that any student conversant with the rudiments of physics and mathematics will be able to read this book and understand what methods are employed for studying the sun and what results have been obtained up to the present.

The study of solar problems has been and is still an interesting one not only to astrophysicists but also to an ever-increasing number of students in various sciences, because the sun, that great distributor of energy and life, undoubtedly exerts a great and varied influence on the phenomena occurring on our earth.

I therefore trust that my labours will not have been in vain, for on the one hand specialists will find here in a nutshell the results of many recent researches and can easily trace the technical works from which they were gleaned, while on the other hand I am convinced that the non-astronomer will gain a comprehensive and general idea of what is known to-day about the sun and of what may reasonably be expected from future studies.

Appended to this volume is a list of the works consulted, which may assist the reader who wishes to go more deeply into the subject. Besides such works, most of the technical essays

that have appeared in astronomical papers have, of course, been considered, such as the *Memorie degli Spettroscopisti Italiani*, continued later in the *Memorie della Società Astronomica Italiana*, the *Monthly Notices of the Royal Astronomical Society*, the *Astrophysical Journal*, the *Zeitschrift für Astrophysik*, and the notices and annals of the various observatories.

I believe that to-day one may safely forecast that solar studies will become increasingly important, not only in reference to astrophysics but also in connection with allied and applied science such as geophysics, biology, agriculture, which are daily calling for extensive and profound knowledge and for a plausible explanation both of solar phenomena and of terrestrial phenomena attributable more or less directly to the sun's influence.

I am much obliged to the translators, Mr. A. V. Zimmermann and Mr. F. Borghouts, and to Dr. R.v.d.R. Woolley, Chief Assistant at The Royal Observatory, Greenwich, for his general technical revision of the English text, and would also like to express my gratitude to those colleagues who were kind enough to send me some of the illustrations.

GIORGIO ABETTI

R Observatory of Arcetri, Florence, (Italy).

1937.

INTRODUCTION

FROM time immemorial the sun has been the object of veneration on the part of all more or less civilized peoples, and with good reason, for if the sun were to fail us, or if the heat it emanates were to undergo even a slight fluctuation, life as we know it on earth could no longer exist. We still find the remains of antique Egyptian temples which, appropriately enough, were dedicated to the cult of the god Ra, the sun, as being a mighty divinity that governs human destiny. The firmament, together with the sun and stars, is depicted in the Bible as being the work of God's hands, an expression of His glory, and the grandeur of Creation.

Apart from this divine and supernatural conception of the sun, the ancients seem to have known nothing definite about its constitution, magnitude, and position in the heavens, though they were familiar with its apparent movements around the earth and among the stars.

It may be stated that the first attempt at physically studying the sun was made by Galileo in 1611, when, without fear of being blinded, he directed his telescope towards the heavenly orb of day. So great was his surprise and his fear of having been mistaken when observing dark points or spots on the sun's immaculate surface, that he hesitated to make his discovery known; meanwhile other scientists, among whom was Fabricius and Father Scheiner, proclaimed the fact independently. This aimed such a severe blow at the prevailing idea of incorruptibility of the heavens and at those who refused to acknowledge the results of observation and experiment, that Galileo proceeded cautiously until he felt certain as to the existence of the phenomenon and how it should be interpreted. Only a year later he was convinced and wrote on the subject, with his well-known precision and clarity, in the following words to the Grand Duke Cosimo II, which appear in his *Discorso intorno alle cose che stanno in sull'acqua:*

"*Repeated observations have finally convinced me that these spots are substances on the surface of the solar body where they are continuously*

produced and where they are also dissolved, some in shorter and others in longer periods. And by the rotation of the sun, which completes its period in about a lunar month, they are carried round the sun; an occurrence important in itself and still more so for its significance."

All is told in a few words: The sun rotates about its axis like the earth, and on its surface there appear from time to time

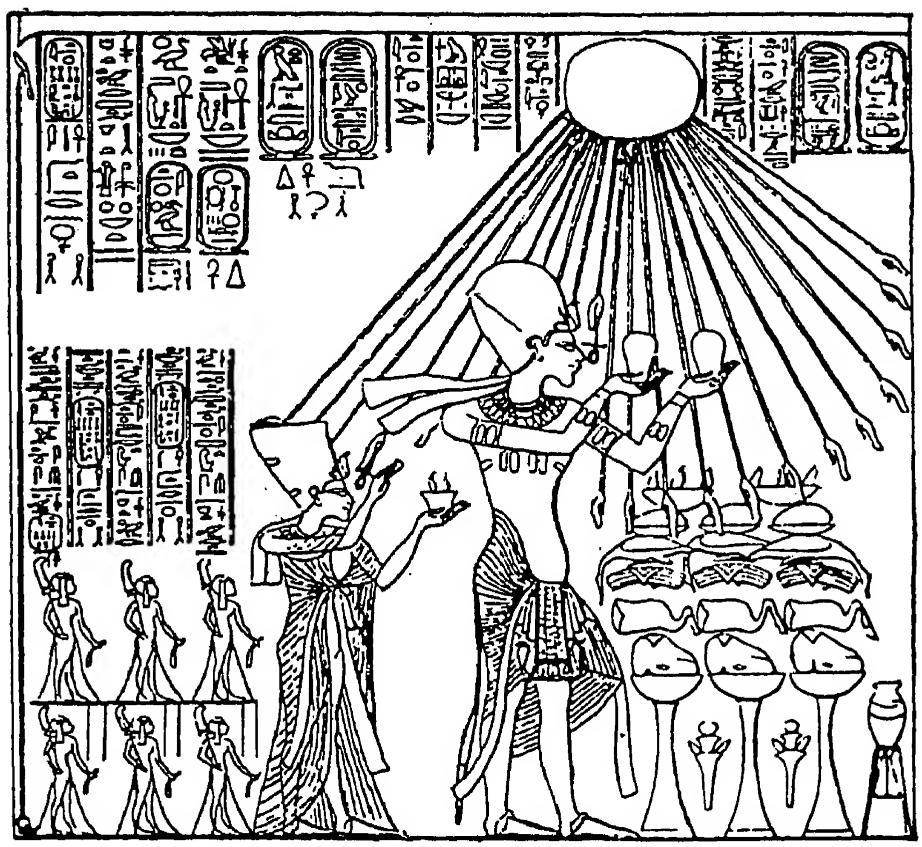

FIG. 1. Akhenaton worshipping the god Ra (the Sun) in 1380 B.C.

spots of varying position and duration, which rotate together with it in such a manner that the sun's period of rotation can be determined from them with an excellent degree of approximation. Of no avail were the discussions and polemics of those who would not see the truth or who chose to think otherwise, like Father Scheiner, who, in the *Tres epistolae de maculis solaribus*, under the pseudonym of *Apelles latens post tabulam*, ruled out the possibility that sunspots could be objects peculiar to the sun's surface.

Galileo replied by his famous *Istoria e dimostrazioni intorno alle macchie solari e loro accidenti*, comprised in three letters to Marco

Welser, in which, while reflecting the conclusions of Father Scheiner, he candidly maintains for the first time the truth of the Copernican doctrine, thus opening the series of his adversities.

At the time of the discovery of sunspots, the sun was about at the maximum of its eleven-yearly period of activity, which maximum probably occurred in the year 1611 or 1612; for this latter year in particular there exist numerous drawings of the solar disc made by Galileo, in which many large spots are to be seen. Occupied with other studies and observations, Galileo

FIG. 2. Sunrise depicted on an Attic chalice of the fifth century B.C.

ceased following the activities of the sun; it was not until many years later, in 1843, that Schwabe of Dessau announced a probable decennial period in the frequency of the spots.

The fact that there were spots on the sun did not at all affect the sense of its perfection. Had not the earth its seas, continents, and mountains? Galileo fully realized this, as well as the fundamental importance of his discoveries regarding the interpretation of the movements of the solar system as compared with the old and no longer tenable hypotheses. He thus pioneered the first physical studies of the constitution of celestial bodies, which were destined in very recent times to culminate in a remarkable development and advancement of astrophysical research.

1. The Importance of Solar Studies

Whilst, after the discovery of the laws of Kepler and that of Newton, it was an established fact that the sun is the ruler of the solar system and that the distances of its planets as well as its dimensions can be determined, nothing could as yet be said about its constitution, viewed both independently and in relation to the "fixed" stars. But when, with the advent of astrophysics, it was found that the sun is nothing but a star similar to so many of those visible in the firmament, there being in fact many stars of a constitution identical with that of the sun, astronomers began to realize the great importance of the researches conducted regarding solar physics in connection with the study of the universe and its evolution.

The sun is seen projected in the heavens as a luminous disc with an apparent diameter of about thirty minutes of arc, thus being a large object for observation, so that with more or less powerful telescopes—and better still, as we shall see, with the spectroscope—the various phenomena occurring on its surface can be examined in detail. The stars, on the other hand, are so far distant from the solar system that they are seen merely as luminous points, even with the most powerful telescopes. Only for some of the most brilliant and nearby stars has it been possible in recent times to determine the diameter by an indirect method (viz. with an interferometer attached to the telescope), which diameter barely attains one-five-hundredth of a second of arc, thus being 36,000 times smaller than that of the sun. So it is futile to expect to be able to distinguish any detail on the surface of the stars, and we must be content with investigating the total amount of light they emit as luminous points. However, if we succeed in concluding from that light that their constitution, or at least that of some of them, is identical with that of the sun, then a great stride will have been made in acquiring knowledge of the universe, since all we find on the sun will be applicable to the evolution of the stars as well.

Where stars of a physical constitution similar to that of the sun are also similar to it in size, it will be realized at what vastly greater distances these stars must be from the earth as compared with the distance of the sun, and consequently

how important it is to learn as much as possible about this self-luminous celestial body, relatively close to us, on which our life depends. Besides studying the sun's physical constitution we shall be able to determine the enormous quantity of energy it sends forth into space and particularly what portion is received by the earth, in what manner this quantity varies with time, and what influence the radiations emitted may have on our globe.

The science of solar physics, from the time when spectroscopic analysis was applied to the study of the heavens, viz. from about 1860, has made very important progress in three-quarters of a century, and it is this progress that we wish to recapitulate in the following pages.

2. Distance and Dimensions of the Sun

Before everything else, we must form a conception of the sun's distance from the earth and of its absolute and relative dimensions.

We have stated that the solar disc measures in the heavens about 30′, which would be equivalent to a disc 6 mm in diameter positioned at a distance of 60 cm from our eye; to be more precise, it should be stated that this apparent size varies according to the position of the earth in its orbit, measuring in January (at perihelion), 32′ 32″, and in July (at aphelion) 31′ 28″.

The sun's parallax, i.e. the angle at which an observer from the centre of the sun's disc would see the equatorial radius of the earth (6378 km), is the fundamental datum which, when known, at once gives the distance of the earth from the sun in kilometres. Several astronomical methods, direct and indirect, agree in giving for the parallax the value 8·8″, and consequently for the distance earth-sun, also termed the astronomical unit of distance, 149½ million kilometres. We may ask ourselves whether and in how far we can be sure of this distance, so important in astronomical calculations. This depends on the precision with which the two data used for deducing it, parallax and terrestrial radius, can be determined. It may be mentioned that nowadays, especially as a result of accurate measurements of the sun's parallax, the distance earth-sun may be considered to be known with

an uncertainty of 15,000 km. This would be the same in practice as if we had a metre measure regarding whose length we were uncertain to within a tenth of a millimetre.

Considering that light travels 300,000 km in a second of time, it follows that a ray of light starting from the sun will take 498 seconds to traverse the distance earth-sun.

In order to form an idea how much greater is the distance of the stars than that of the earth from the sun, we must have recourse to what is called the parallax of the fixed stars or, to be more exact, the *annual parallax*, viz. the angle at which, from the star, an observer would see the radius of the terrestrial orbit. From an examination of the star α *Centauri* which we know to be the nearest to the solar system, with a parallax equal to $0 \cdot 75''$, we can calculate that its light takes $4 \cdot 3$ years to reach our earth. Consequently the sun, considered as a fixed star, is just as much closer to the earth than the nearest of the other stars as is the ratio between $4 \cdot 3$ light-years and 498 seconds, viz. more than 270,000 times closer.

Knowing the mean distance and the mean apparent diameter of the sun, we can at once determine its radius, which is found to be 695,450 km, viz. 109 times the earth's radius; consequently the sun has a volume one million three hundred thousand times greater than that of the earth. With the values of the mean diameter of the sun in seconds of arc, $1,920''$, and the diameter in kilometres, 1,390,900, it follows that an object on the sun's surface which is seen from the earth at an angle of $1''$, has a real spread of 725 km. This measurement will be of use to us in judging the magnitude of the various phenomena observed on the sun.

Moreover, in order to determine whether the sun is made of more or less dense materials than the earth, we must also determine its mass. The law of universal gravitation gives us a method of expressing the sun's mass as a function of the quantities that characterize the earth's movement around the sun. If we suppose, with sufficient approximation for our calculation, that the earth's orbit is circular, then we can equate the centripetal acceleration at which the earth is subjected to the attractive force acting between sun and earth according to Newton's law. Knowing the constant of universal attraction, we find that the mass of the sun is 332,000 times

greater than that of the earth. If the earth weighed three grams, then the sun would weigh a ton. So we see from these figures how small the earth is compared with the sun; on the other hand the earth has a much greater density, for if we compare the ratio of the volumes (1,300,000) with that of the masses (332,000), we find that the earth is about four times denser than the sun. Since the mean density of the earth is 5·5 times that of water, it follows that, if we take the density of water as unity, the density of the sun will be 1·4.

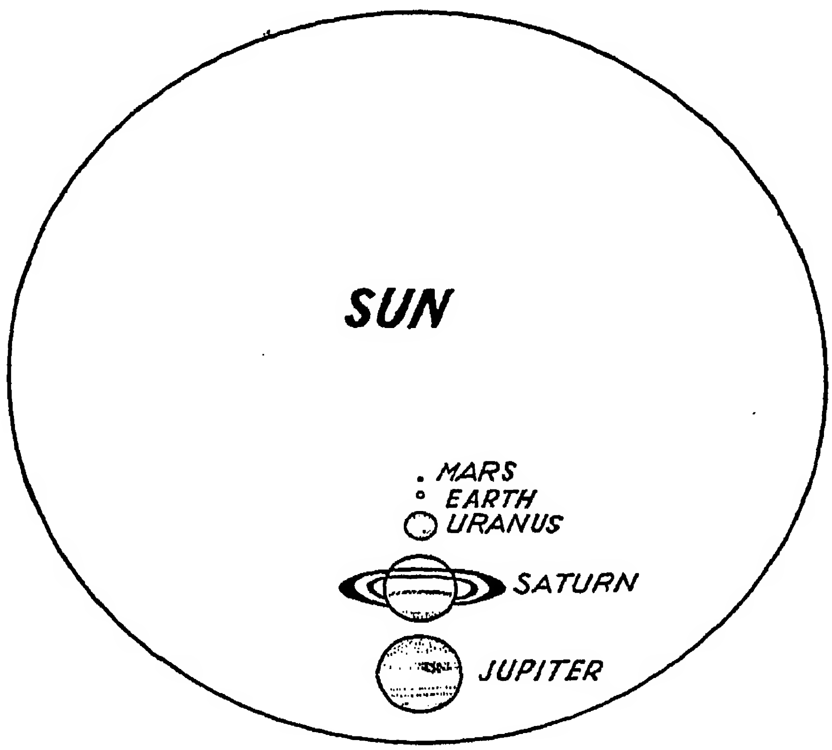

Fig. 3. Comparison between the dimensions of the sun and of some of the planets.

We thus begin to realize that the sun cannot be in a solid condition, since the materials of which it is composed are on an average considerably less dense than the solid materials of which the earth is constituted.

With these results it can furthermore be calculated to what extent gravity at the sun's surface exceeds that on the earth. The ratio of the two forces is approximately found by dividing the ratio of the two masses by the square of the ratio of the two radii. It is thus found that gravity on the sun is about twenty-eight times greater than on the earth, and consequently, whilst on the earth a falling body traverses about 5 metres in the first second, it will traverse 140 metres on the sun.

CHAPTER I

HOW THE SUN IS OBSERVED

Visual and Photographic Telescopes. Helioscopes

Any astronomical telescope is suitable for visual observation of the sun, whether it be a refractor with an achromatic visual lens or a reflector with a parabolic mirror.

The image produced by the telescope, in the focus of the object-glass or mirror, is all the smaller and all the more intense the smaller its focal length. Indeed, since the ratio of the diameter of the image to the real diameter of the sun is equal to the ratio between the focal length of the object-glass (or mirror) and the distance of the object, it can be calculated, for instance, that an object-glass or a mirror of one metre focal length gives a solar image of one centimetre diameter, an object-glass or mirror of two metres focal length gives an image of two centimetres diameter, and so on. This image may be observed directly with an ordinary eye-piece, which in turn gives of this image a virtual inverted and enlarged image, or may be observed with the same eye-piece by projection. A means is obviously needed for softening the image, which is so intense that it would otherwise injure the eye, so in front of the eye-piece we fit a "helioscope," an instrument which in its simplest form consists of a tinted glass slip with its two surfaces perfectly parallel. As a rule dark glass is used, which admits a small portion of rays of such refrangibility as to give a whitish, slightly smoked image of the sun, or use is made of reflected or polarized light, as in the helioscope designed by Herschel and by P. Cavalleri. Another type of helioscope is that of Colzi, in which the sun's image is softened when passing through a double prism consisting of a rectangular glass prism and a liquid prism (also rectangular). The beam of rays, after having been reflected by a glass slip at S (Fig. 5), enters the glass prism B and would be totally reflected but for the liquid prism C. But since at C there is vaseline oil, whose index of refraction only differs very slightly

from that of glass, it follows that the rays are faintly reflected on the hypotenuse of prism B and that the solar image reaches the observer's eye in a sufficiently subdued condition.

We can observe by projection the image given by the telescope on a screen, as was done by Galileo and Father Scheiner (Figs. 7 and 8), and this method is very convenient when we wish to depict the phenomena presented by the sun's surface. For this we simply move the eye-piece farther away from the focal plane of the object-glass or mirror until the solar image comes into the focus on the screen, which is placed at a convenient distance from the eye-piece. The diameter of the image obtained on the screen depends on the ratio between the distance of the screen from the eye-piece and the focal length of the eye-piece itself, multiplied by the diameter of the image given by the object-glass or mirror.

FIG. 4. Colzi's helioscopic eye-piece.

If, on the other hand, we wish to photograph the solar image, we can simply place the photographic plate at the focus of the telescope, but where a refracting telescope is used, it is desirable that the object-glass should be a photographic one, which brings violet and visible rays to the same focus; otherwise, if a visual object-glass is used, it will be advisable to take the photograph with a screen that eliminates these radiations. In any case, unless the telescope used is of large focal length,

the image of the sun at the principal focus will prove small and it will be desirable to enlarge it (as is done by projection in the case of visual observations), by exposing the photographic plate instead of the screen. Telescopes constructed for this purpose are also called "heliographs."

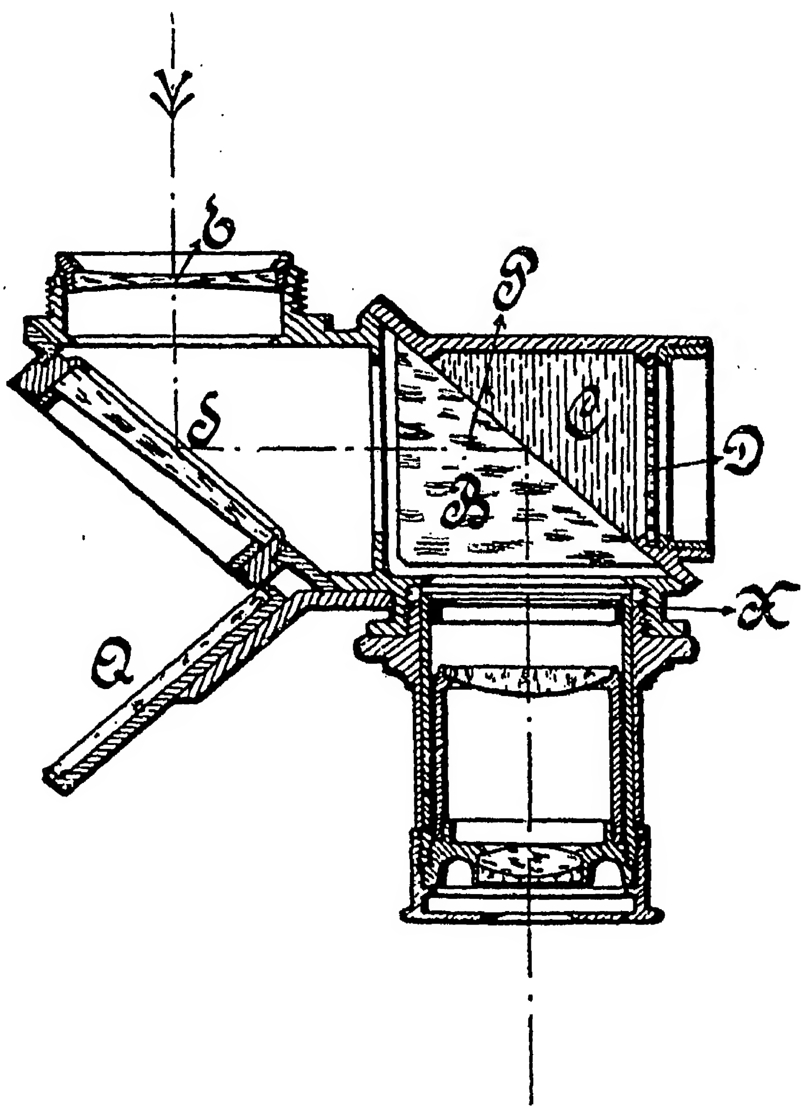

FIG. 5. Diagram of Colzi's helioscopic eye-piece.

If a bright and fair-sized image of the sun is desired in order to distinguish the various details on it, it will be necessary for the reasons explained above to have telescopes of large focal length. If, moreover, it is proposed to fit them with spectrographs of large dispersion, viz. also with a considerable focal length, it is obvious that the moving system consisting of the telescope and spectroscope may prove to be of unwieldy

or even prohibitive dimensions. So the plan has been devised of constructing long telescopes, fixed horizontally or vertically, in which the sun is reflected during all hours of the day by one or more plane mirrors inclined at suitable angles.

Of the horizontal type there is, for instance, the Snow tele-

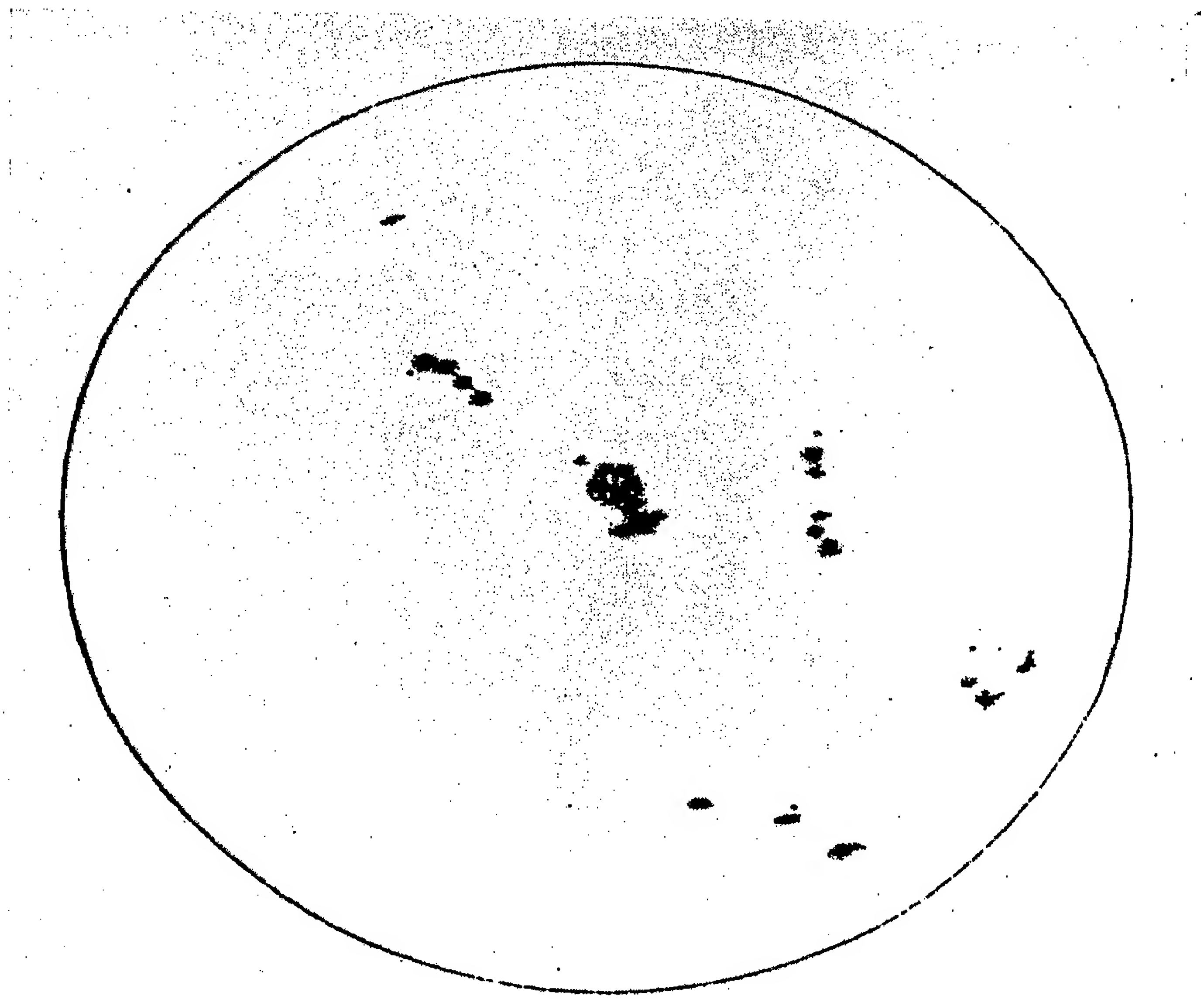

FIG. 6. The large spots observed by Galileo at Florence in August 1612.

scope at the Mount Wilson Observatory in California, which is a reflector, and several refractors at the Meudon Observatory in France.

The Snow telescope consists of a first plane mirror, also called a coelostat (Fig. 9 (I)), a second plane mirror (II) and a concave mirror, which gives the solar image S at S'.

The coelostat and the second mirror reflect the sun's light

FIG. 7. Frontispiece to volume III of *Rosa Ursina*, Bracciano, 1626.
(In the lower part is to be seen the method used by Father Scheiner for observing the sun.)

in a constant direction at all seasons and at all times of the day; the coelostat is therefore driven by a clockwork mechanism and is mounted on an axle parallel to the earth's axis in

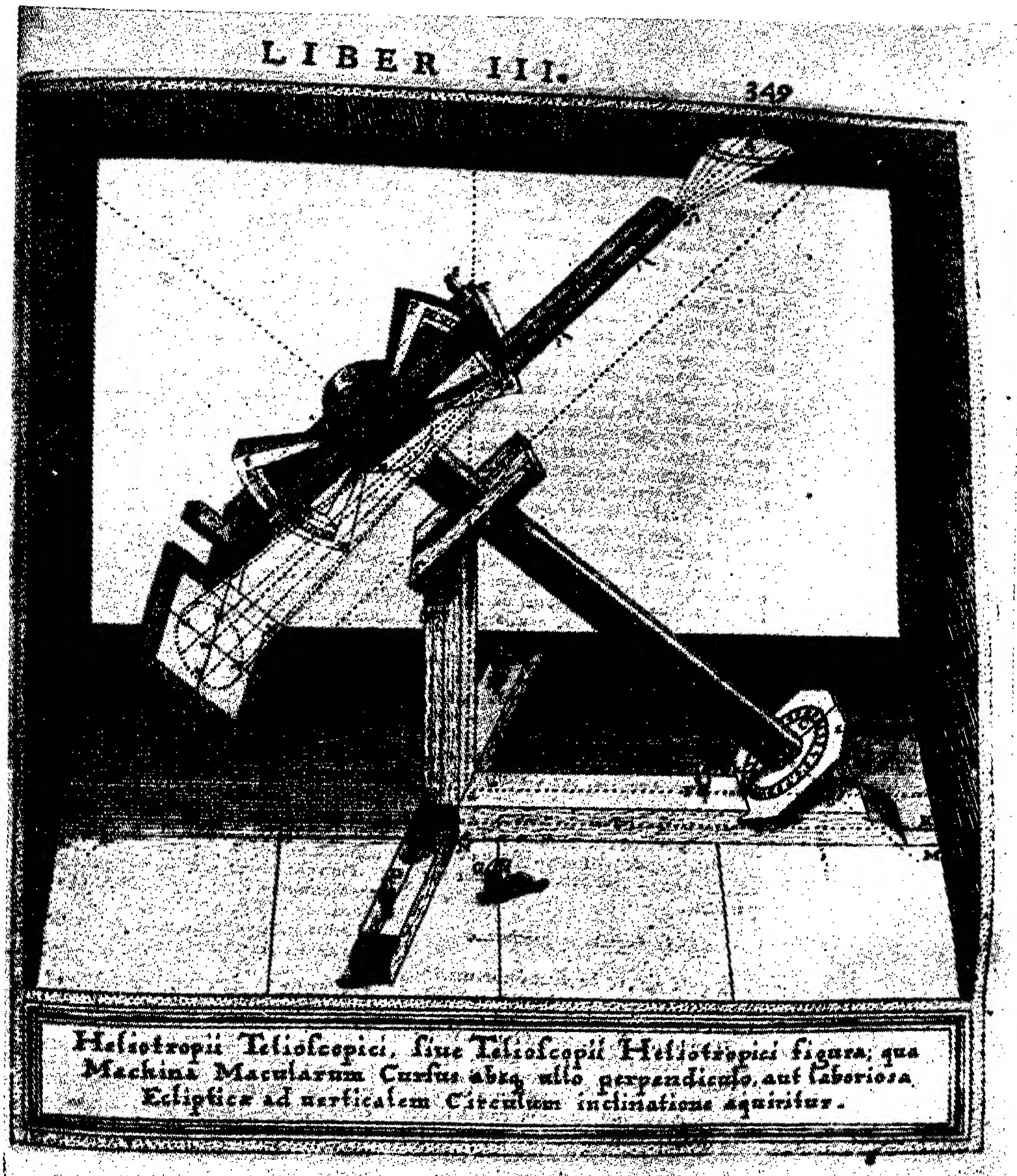

FIG. 8. Equatorial installation used by Father Scheiner for observing the sun.
(From volume III of *Rosa Ursina*.)

such a manner as to follow the sun in its apparent diurnal motion. The coelostat can be moved on rails in the direction

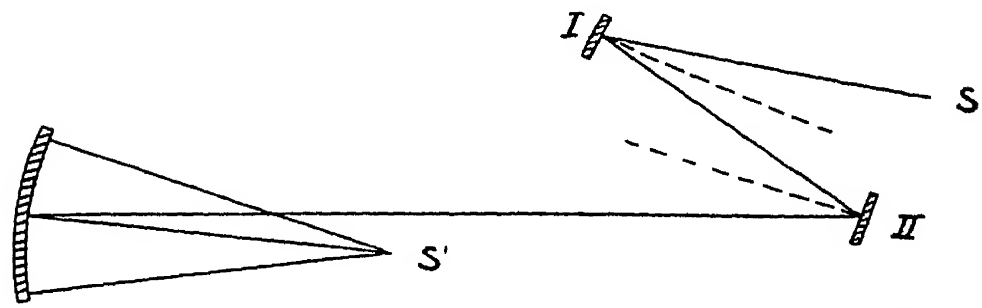

FIG. 9. Diagram of the Snow horizontal telescope.

east-west, the second mirror in the direction north-south, so that the concave mirror is always completely illuminated at

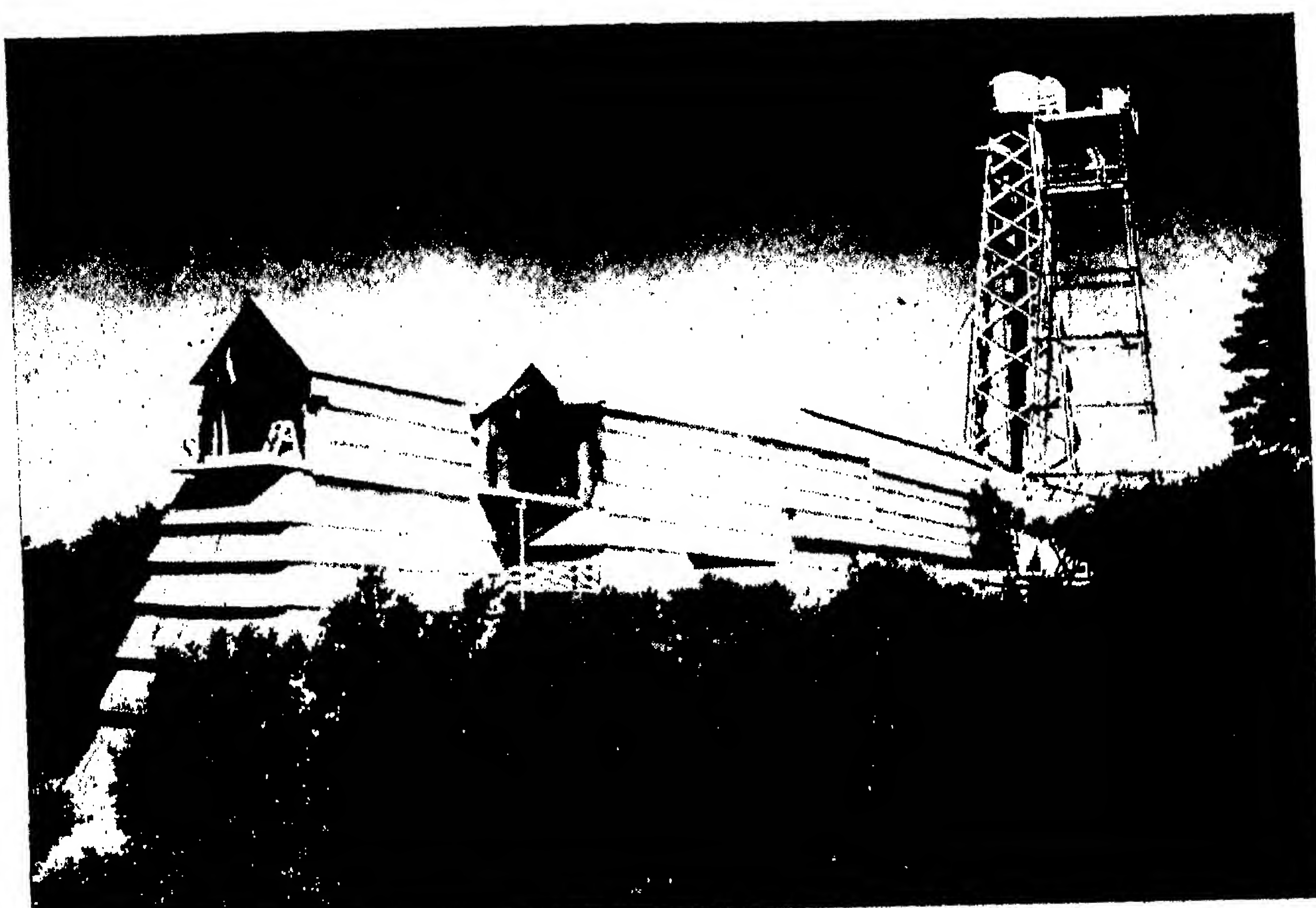

FIG. 10. The Snow horizontal telescope (external view) and the two solar towers of the Mount Wilson Observatory (California).

various hour angles and at various declinations of the sun. The light reflected by the plane mirrors is combined into an image by the concave mirror, which has an aperture of 61 cm

and a focal length of 18 m, and is lodged at the back of a pavilion with an iron framework, covered with white linen

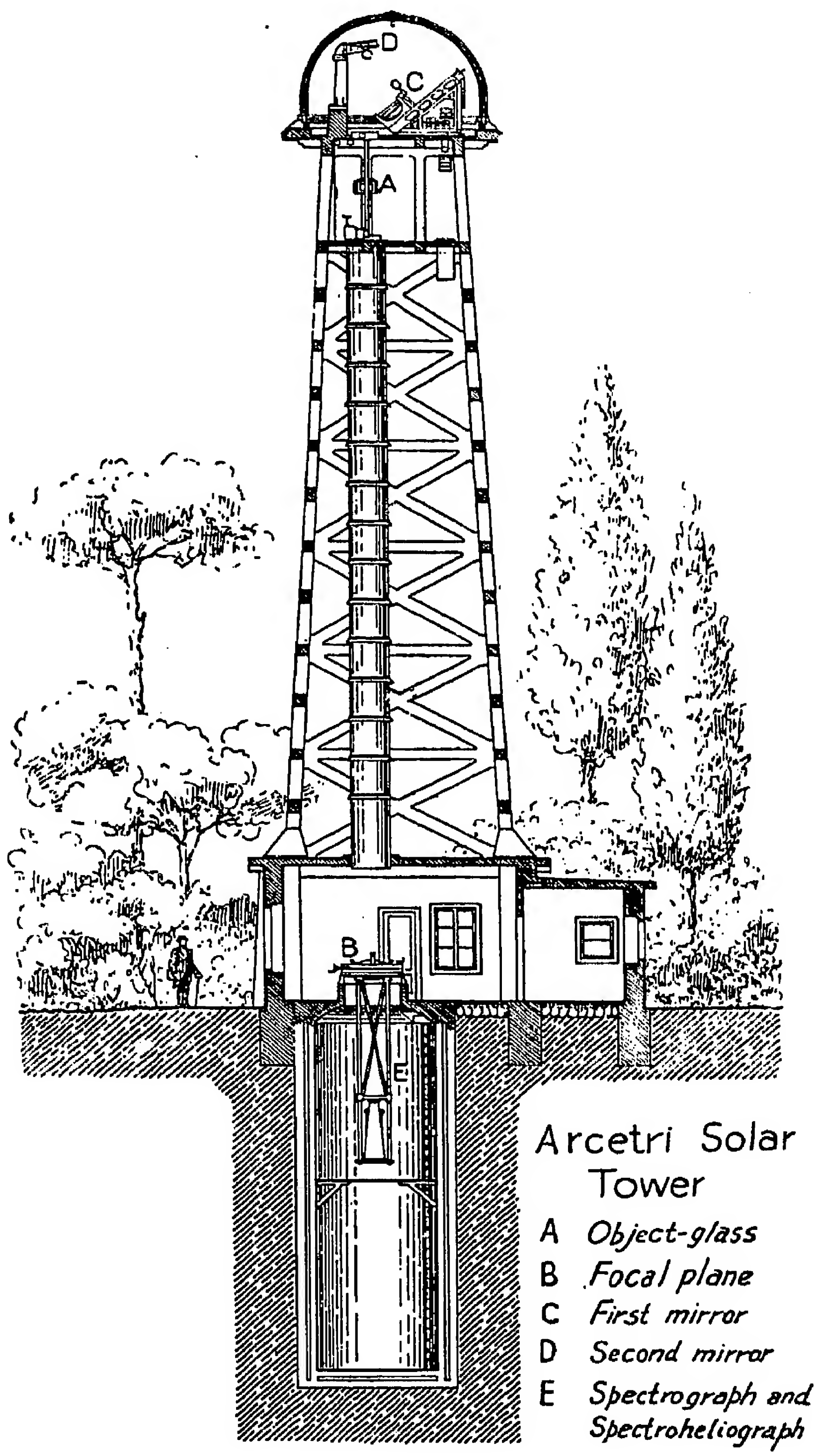

FIG. 11. Diagram of solar tower at Arcetri (Florence).

and well ventilated to prevent detrimental heating. The solar image at the focus of the concave mirror at S' has a diameter of about 17 cm and can be directly photographed at that

spot by means of the spectrograph and the spectroheliograph, as we shall explain in the following lines.

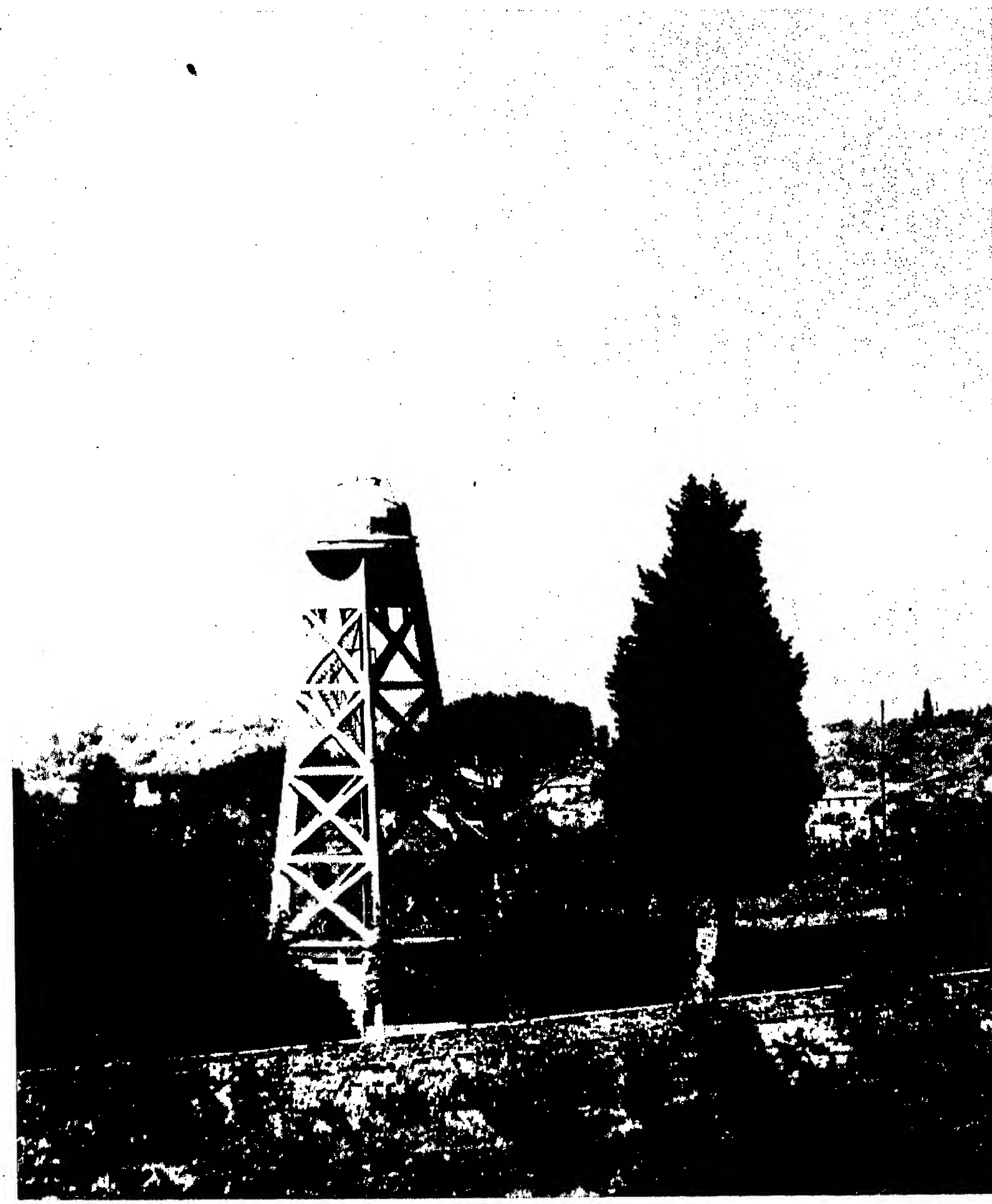

FIG. 12. Solar tower of the R. Observatory at Arcetri (Florence).

The fixed telescope of vertical type was first constructed by G. E. Hale and is called the "Solar Tower." The refractor

or reflector, placed vertically in a fixed position, receives the sun's light from a coelostat and from a second mirror, both situated at the top of the tower. There are solar towers in the

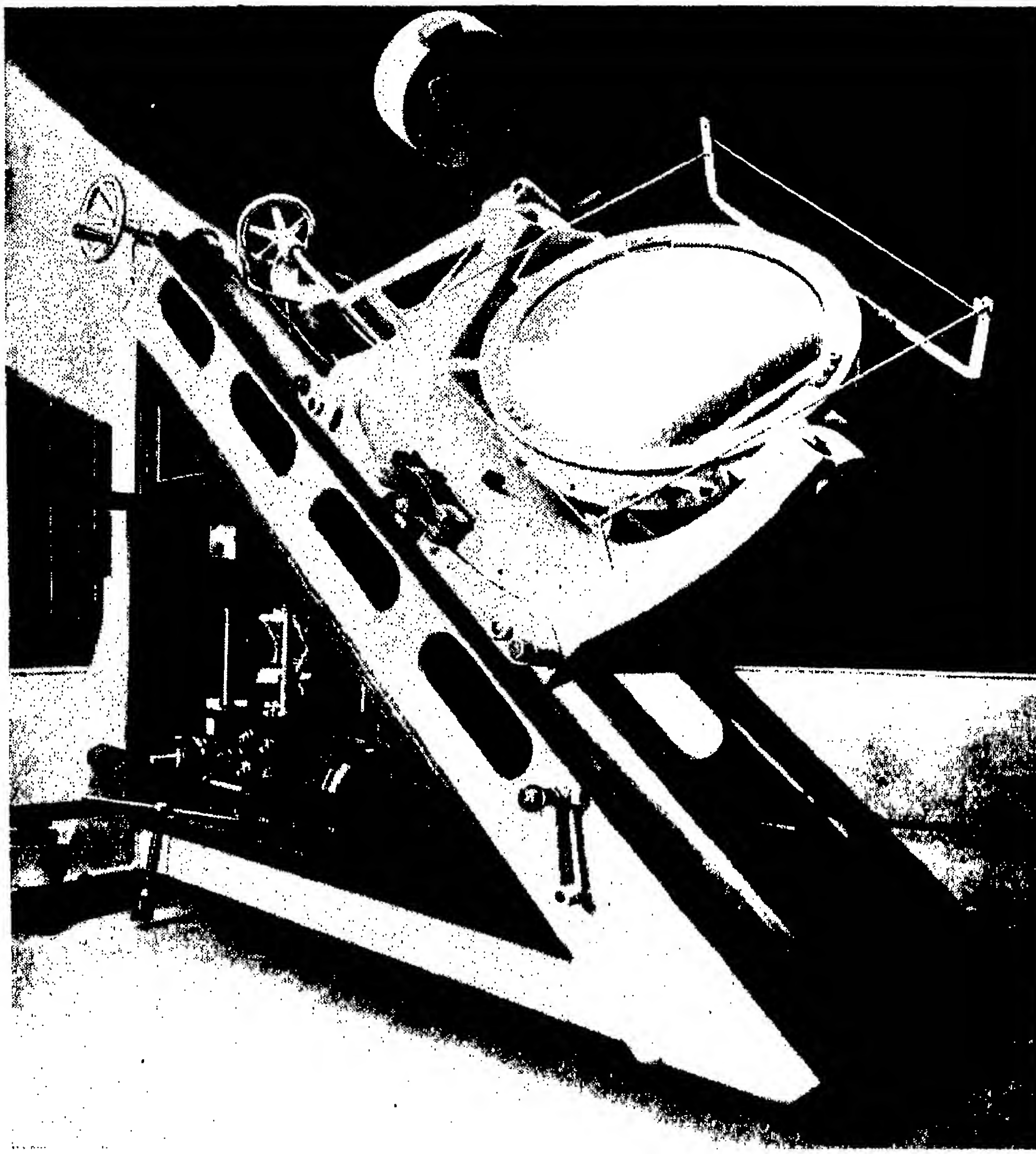

FIG. 13. Coelostat of the Arcetri tower.
(Mirror C in Fig. 11.)

Mount Wilson Observatories as well as at Arcetri (Florence) and Potsdam. We will describe the one at Arcetri.

The general arrangement of the various parts of this tower, which is of the refracting type, is seen in Fig. 11. In the top part of the tower, protected by a revolving dome, are the coelostat C (Fig. 13) and the second mirror D. Underneath the mirror at A is an astronomical lens with an aperture of

30 cm and a focal length of 18 m, so that at B a real image of the sun measuring 17 cm in diameter is obtained. At B the vertical telescope ends and here commences, in a pit dug in the ground along the axis of the tower, the instrument used for splitting up the sun's light into its spectrum.

The object-glass at the top of the tower can be removed from the top in a downward direction by electrical mechanism

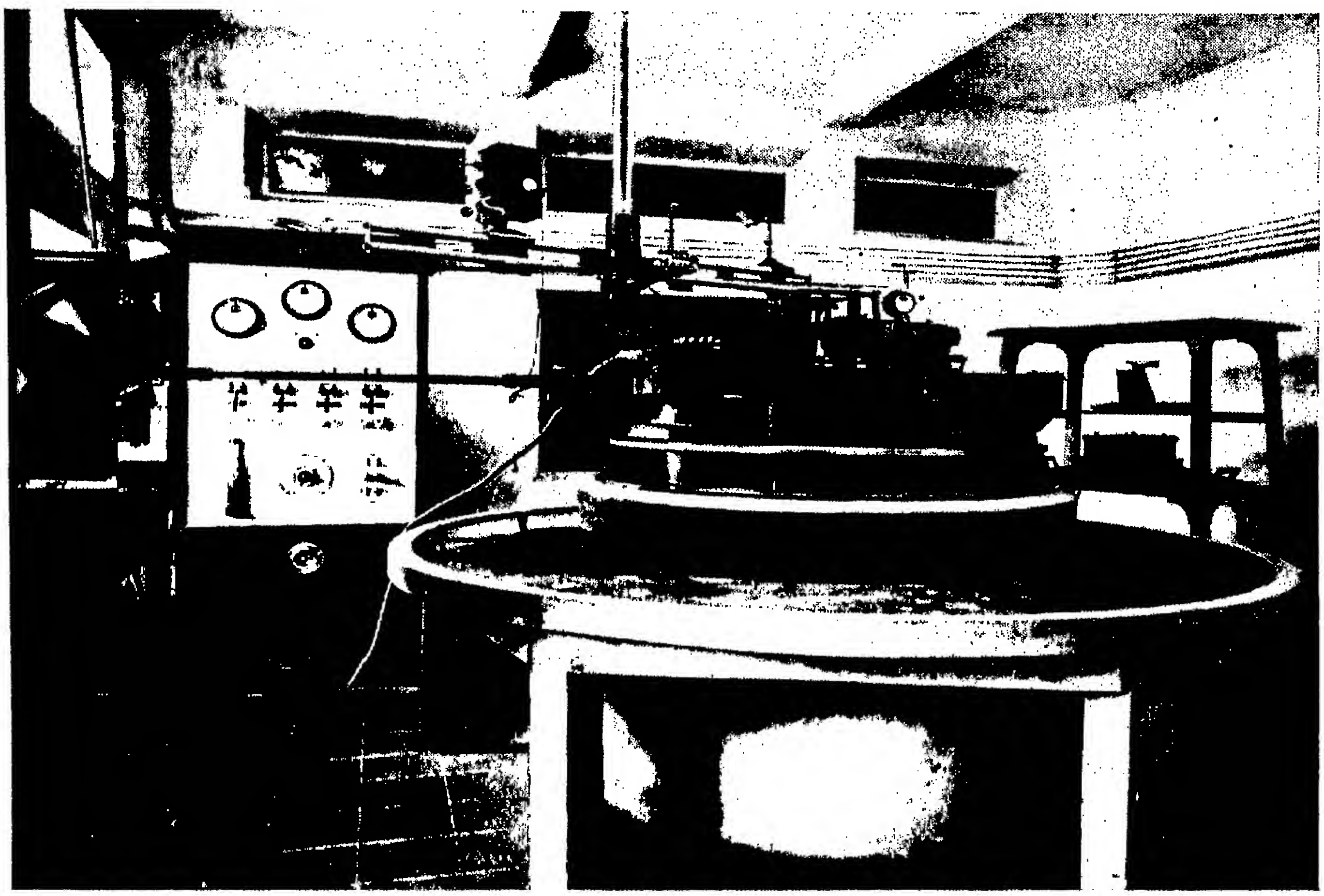

FIG. 14. Observation room of the Arcetri tower, showing the upper part of the spectrograph and spectroheliograph. (Attached to the ceiling is the comparison arc.)

controlled from the observation room at the base of the tower, so that the observer may vary its focus and bring the image into focus on plane B, where the slit of the spectroscope is situated. There are also electrical devices for moving the mirrors so that the particular region of the sun that one wishes to observe is brought on to the slit of the spectroscope.

The object-glass in the top part of the tower may be replaced by another at a distance of seven metres above the plane of B, with this focal length, so that on the slit of the spectroscopes

there is a solar image measuring about seven centimetres in diameter. We thus have in the same tower two telescopes giving respectively two solar images of different sizes, enabling the observer to conduct researches of varying nature.

To eliminate the effect of vibration due to winds the larger tower at Mount Wilson consists of two iron towers, one enclosed within the members of the other. The outer tower supports the dome and protects the inner one, which carries the mirrors.

FIG. 15. How the sun is observed at the Arcetri tower.

In the Potsdam tower the mirrors are supported by a wooden structure in the interior of a concrete tower. The Arcetri tower is a simple reinforced concrete construction with a lattice-work, and it has been found that in winds of moderate intensity there is no appreciable vibration to affect the sun's image.

Spectroscopes, Spectrographs, Spectroheliographs, Spectrohelioscopes

These designations apply to instruments used for visual or photographic observation of the solar spectrum and its monochromatic radiations. If we decompose a beam of solar rays

with a prism, we see its ordered spectrum with colours running from violet to red. If we desire a "pure" spectrum, viz. one in which we can see the lines observed for the first time by Fraunhofer in 1814 and named after him, we must pass through the prism a beam of solar rays which has been limited by a slit and made parallel by means of a lens called the "collimator." At the end of the prism the coloured rays are collected by another lens that gives an image of the spectrum, which in its turn is seen enlarged by means of an eye-piece. This entity comprising slit, lenses and prism, forms the "spectroscope," so called because it serves for visual observation of the spectrum.

If, on the other hand, we wish to make photographic observations, we must substitute for the eye-piece a photographic plate on which we shall obtain a photograph of the solar spectrum with a length depending on the dispersive power of the prism and on the focal length of the object-glass of the camera by which the image is produced on the plate, the intensity being variable according to the sensitivity of the plate to the various colours. These instruments are termed "spectrographs," because they serve for photographing the image of the spectrum.

We describe as "spectroheliographs" and "spectrohelioscopes" the instruments used for photographing or observing the solar spectrum with a specific monochromatic radiation, viz. that of one of the Fraunhofer lines, which for special reasons are of interest for investigation. Once this line becomes isolated from the remaining spectrum, it is possible, with these instruments, either to photograph it or to examine it visually on the whole solar disc.

Up to now we have been discussing the use of a prism in the instruments referred to, but if we wish to increase the dispersion and thus have a more extensive spectrum we must use more prisms in succession. A combination or "train" of such prisms in which, with a judicious choice of glasses of different indices of refraction, the spectrum is observed in the direction of the incident ray, i.e. without deviation, constitutes what is called the "direct-vision prism" of G. B. Amici.

Instead of the prism or prisms we may use a diffraction grating as a means of dispersion. As the history of diffraction

gratings, especially on account of the use made of them in astrophysics, is interesting and comparatively little known, we will briefly summarize this history and explain at the same time how these gratings are used.

The discoverer of the phenomena of diffraction was, as is known, Father Grimaldi, but the first gratings for obtaining the spectrum of a luminous source by means of diffraction were not constructed until many years later by Fraunhofer. He conceived the idea of using, instead of only two slits as used for producing interference phenomena, a series of slits at equal distances apart. The first grating constructed by him in 1821 consisted of a silver filament wound around a brass frame. Of course he took great care to ensure that the spacing between the turns of the filament was as uniform as possible, an indispensable condition for obtaining pure spectra.

Fraunhofer succeeded later in constructing gratings by engraving a large number of parallel and equidistant lines on a glass plate; he succeeded in engraving up to 300 lines in one millimetre. If in a spectroscope we substitute for the prism or prisms a plate engraved in this manner, and observe through its telescope, pointed perpendicularly to the plane of the grating, we shall see the image of the slit illuminated by a light-source, and when moving the telescope at different angles to the right or to the left we shall see in a regular arrangement on either side a series of spectra described as being of first, second, third or higher order, each arranged with its violet end nearest the direct image of the light-source and the red end away from the direct image.

Whilst, therefore, with the prism we have one spectrum only, in this case we have a series of spectra of an intensity gradually decreasing as the order increases, but nevertheless, in view of the great dispersion that a grating may give and owing to the fact that in the spectra produced by it the deviations are proportional to the wavelength, gratings are preferable to prisms when we have a sufficiently intense light-source as in the case of the sun.

Rutherfurd in New York was the first to obtain, by silver-plating a glass plate, "reflecting gratings" that give the spectrum by reflection instead of by transmission. He was also able to engrave these gratings, not on a glass plate but on a

specular metallic surface, viz. on a metal called "speculum," which is an alloy of brass and tin with the addition of a little arsenic to increase its whiteness. This metallic surface offers the advantage of being more easily divided, since it is softer

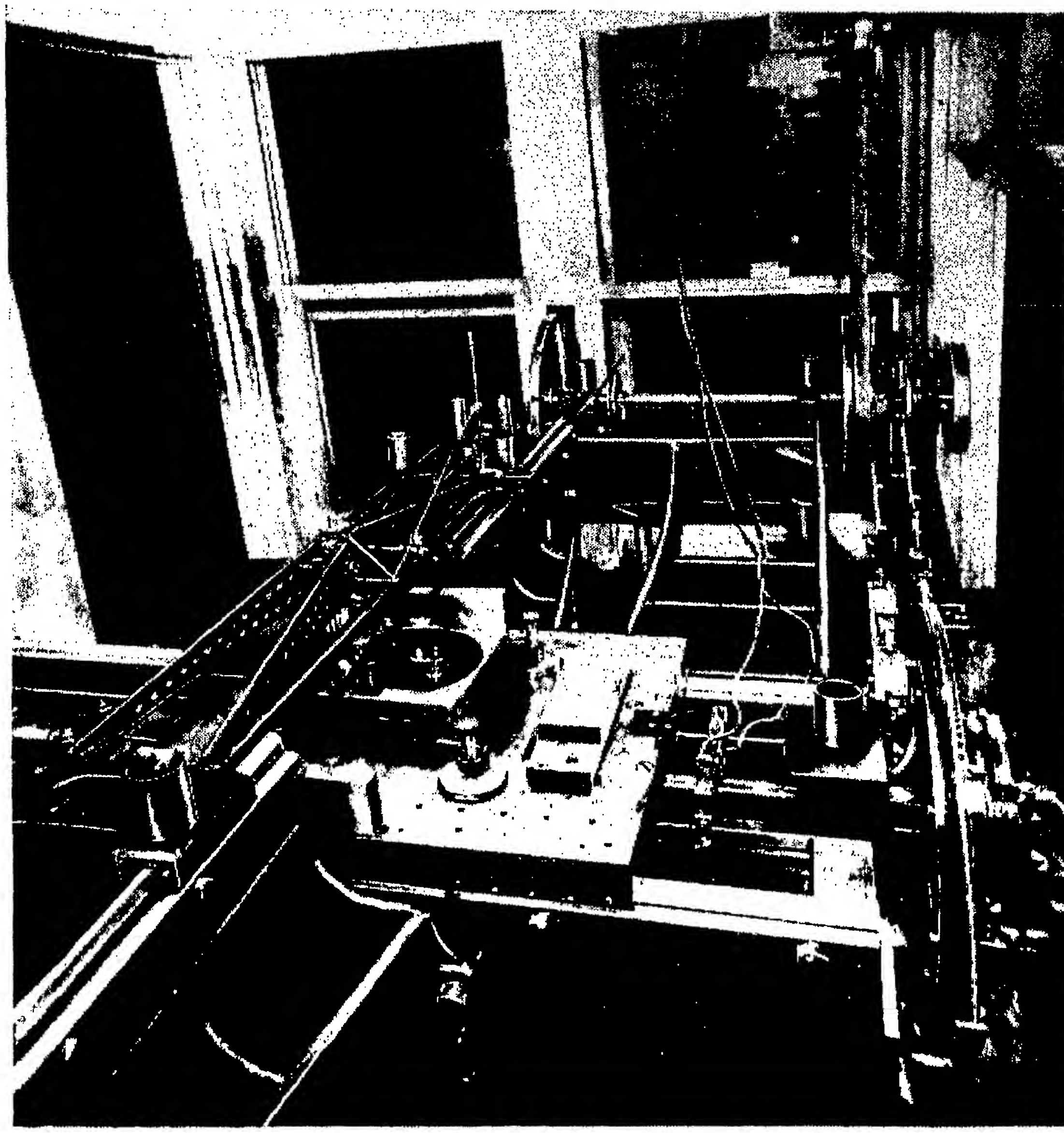

FIG. 16. Machine for ruling diffraction gratings at the Mount Wilson Observatory, constructed by C. Jacomini.
(On the machine a grating of 20 cm in diameter can be seen in the process of ruling.)

than glass, and it does not so greatly wear down the point of the diamond used for engraving the numerous lines.

The American physicist H. Rowland succeeded in obtaining with a special machine of his own construction a very great precision in the construction of these reflecting gratings by tracing up to 4,000 lines in 1 mm on plates of flat metal and

also on concave mirrors possessing a certain focal length, and thus obviating by means of these concave mirrors the use of lenses for focussing the image of the spectra. The great precision obtained by Rowland is due to his having used a perfect

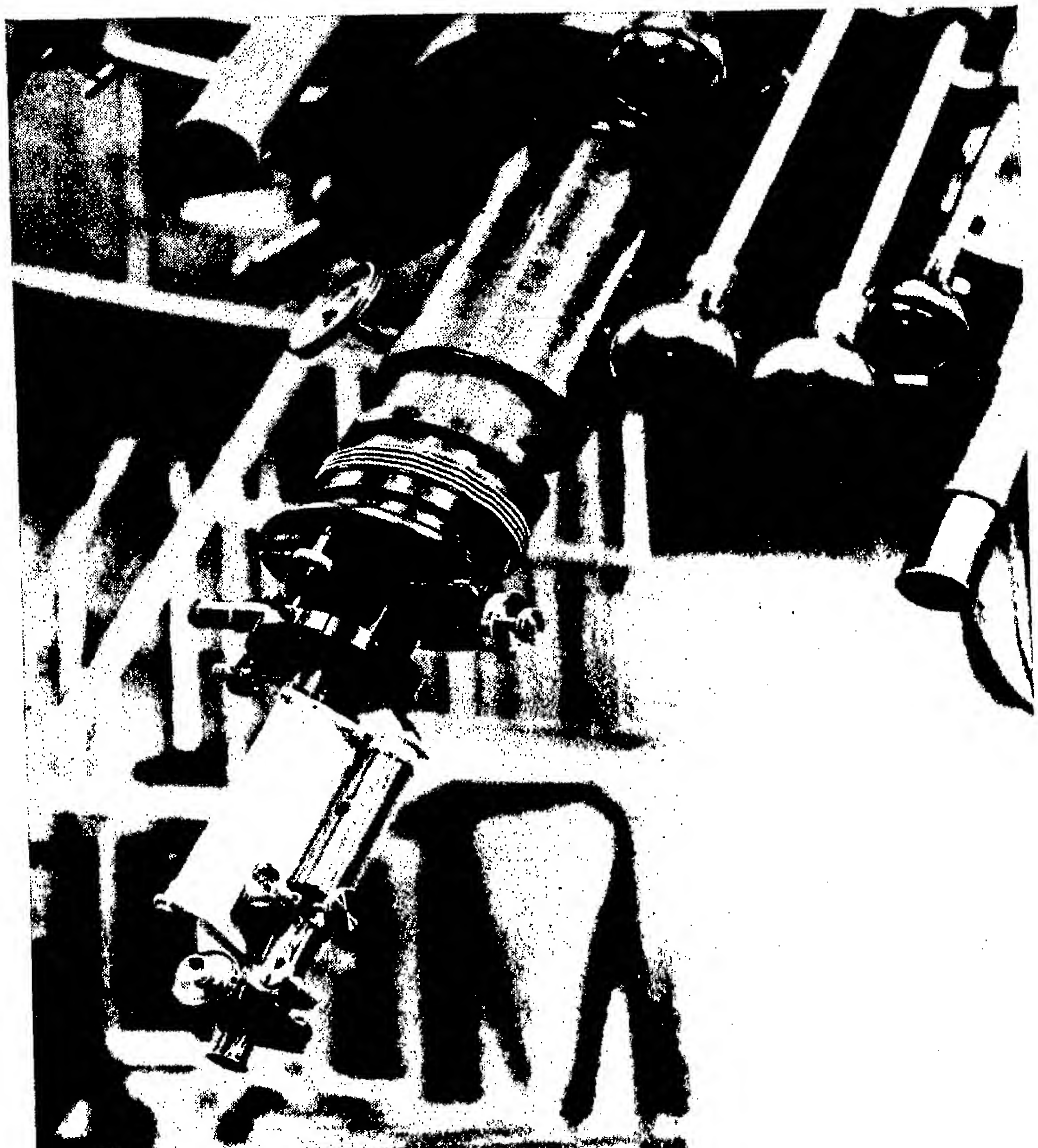

FIG. 17. Spectroscope for prominences, fitted to Amici's equatorial. (R. Observatory of Arcetri.)

screw to shift the point of the diamond serving for ruling the lines, and also to his careful shaping of the point of the diamond and of the various parts of the dividing machine. His numerous gratings, which are largely used in astrophysical

research, generally have 600 lines per millimetre. Notwithstanding the progress of mechanics the technique of obtaining good gratings is still rather difficult, and for this reason there are but few really good gratings constructed since Rowland's time. Good gratings of large size have been and are still being

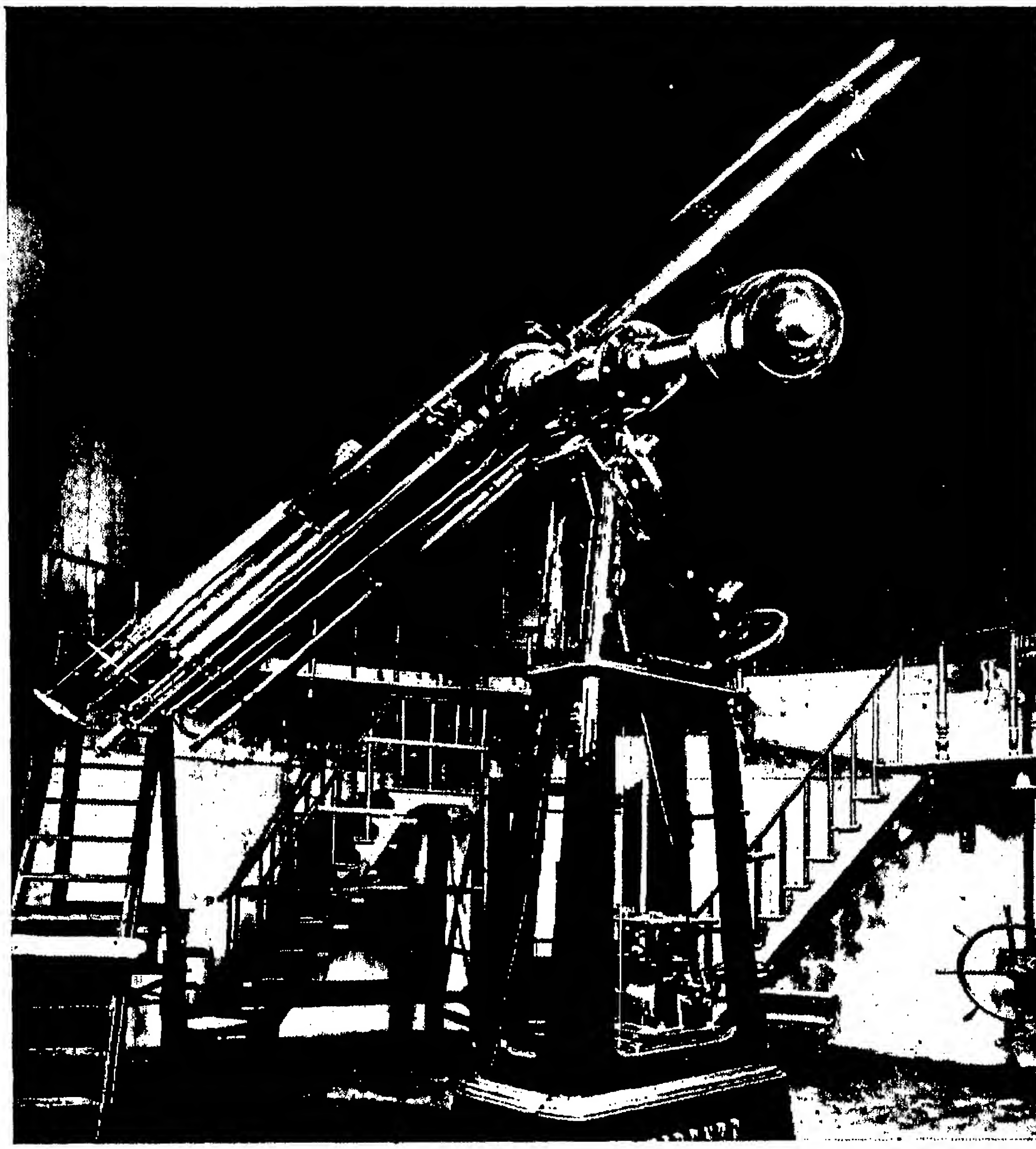

FIG. 18. Amici's equatorial with solar spectroscope and finder for observing the sun by projection.

made at the laboratory of the Mount Wilson Observatory, with a machine constructed by C. Jacomini (Fig. 16).

The grating used at the Arcetri tower was also engraved by Jacomini with such a machine, and has a ruled surface of 10 × 11 cm, with 600 lines per millimetre, i.e. with a total

of 66,000 lines. The form of the lines ruled by the diamond has been so selected that the light is for the most part concentrated on one of the spectra of the first order, which renders it particularly suitable for observations with the spectroheliograph.

We will now refer to the types of spectroscopes, spectrographs, etc., most commonly used for observation of the sun.

The types of spectroscopes adopted by the first investigators are still being used to-day with but little alteration, particularly for observing prominences on the solar limb (Fig. 17). The dispersive device generally consists of a direct vision prism of Amici, and the axis of the spectroscope is shifted parallel to the optical axis of the telescope, by an amount equal to the radius of the solar image at the focus, so that, once the slit is directed tangentially to the solar limb, it continues to remain tangential to the solar limb while the spectroscope is turned. The position angle which the slit takes up as the spectroscope is turned, is read on a special graduated circle, and in this way we can easily make an examination of the entire solar limb.

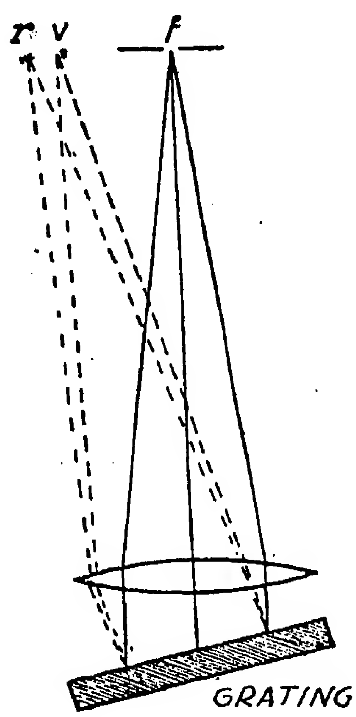

FIG. 19. Diagram of auto-collimating spectrograph.

Spectographs are generally of larger dimensions and are used in conjunction with the horizontal and vertical telescopes we have mentioned.

The photographic method is a useful, indispensable complement of the visual one, and offers several advantages over the latter. As a matter of fact, observation with the spectrograph is extended beyond the limit of the violet and red radiations which are visible to the eye; we can make long exposures with very large dispersion and a large number of Fraunhofer lines, and their characteristics, which can easily be measured later on, are recorded on the plate. The dispersive means used are, according to the case concerned, gratings or prisms or a combination of the two; with the grating a form of apparatus often used is that represented in Fig. 19, in which a single lens, called "the

auto-collimator," serves as collimator and as object-glass for the photographic camera.

The dispersion produced by a grating depends on the order of the spectrum used and on the number of lines engraved per millimetre; but the scale of the spectrum on the photographic plate depends further on the focal length of the lens of the spectrograph.

In the spectrograph of the great tower of Mount Wilson, which has a focal length of 23 metres, an *angstrom*, the unit of wavelength measurement (equal to one ten-millionth of a millimetre), appears on the plate as equal to five millimetres in the third order of the grating used, so that the two sodium lines D_1 and D_2 are three centimetres apart.

As already stated, the spectroheliograph is merely a spectrograph, but one by means of which we can isolate the radiation of a given wavelength, such as a Fraunhofer line, and study it over the entire solar disc. Following up this conception and with a view to photographing the solar prominences, Hale was the first to obtain a positive result. In 1892 he was able to present the first photograph of the chromosphere and prominences surrounding the solar disc, in one of the radiations emitted by the incandescent vapour of calcium. The procedure for obtaining this result is as follows:

Imagine an ordinary spectrograph in which is mounted, in front of the photographic plate, a second slit that isolates a specific region of the spectrum, as for instance one of its absorption lines. Only the solar radiation corresponding to that particular wavelength will then be allowed to pass and affect the photographic plate, which is placed almost in contact with the second slit.

When, therefore, the whole instrument is moved in such a manner that its optical axis continuously occupies successive positions, always remaining parallel to itself and traversing the entire image of the sun, we shall obtain on the plate an image which may be called *monochromatic*, or rather, one which corresponds to the radiations absorbed in the spectrum by the line under examination.

Evidently this image represents the integration of the whole solar disc formed by the successive images of the first slit. For this it is necessary that the relative motion of the solar

image with respect to the first slit, or vice versa, be such that the light of all the regions of the disc passes successively through the first slit, whilst the photographic plate undergoes a corresponding relative motion with respect to the second slit, or vice versa. This serves for isolating only the desired line, and consequently its breadth must be exactly that of the line itself, excluding the light coming from the other parts of the spectrum. The good results obtained by Hale are essentially due to the fact that it occurred to him to use the lines H and K of calcium, viz. the most intense lines of the solar spectrum in the extreme violet region, little adapted for visual observation but very suitable for photographic observation. Their exceptional intensity, the presence of the broad dark bands which accompany them and which considerably diminish the brightness of the continuous spectrum, and the high sensitivity of photographic plates to this wavelength, are reasons why these two lines are very suitable for the spectroheliograph.

,,hen, thanks to the rapid progress of photography, one could obtain plates sensitive also to the red region of the spectrum, it was also found possible to use the red hydrogen line *Hα*, which, on account of its intensity and the importance of this gas in solar physics, soon led to substantial results.

We will now refer to the most commonly used type of spectroheliograph. This instrument, originally designed for photographing solar prominences, finds nowadays a much wider field of application.

The spectroheliograph can be fixed to reflectors or to refractors, and when of considerable dimensions it can advantageously be applied to horizontal or vertical fixed telescopes.

The various types of spectroheliographs differ in so far as the solar image and the photographic plate may be kept fixed, the whole spectroheliograph being made to move, or the spectroheliograph may be fixed and the sun made to move in front of the first slit, the photographic plate being moved in front of the second slit.

To the first type belongs the spectroheliograph of the Arcetri solar tower, which is combined with the spectrograph. The first slit A and the second slit B (Figs. 20 and 21) are supported by a platform which can turn on a vertical axle

and be shifted horizontally with uniform motion for an interval equal to the diameter of the solar image (17 cm) given by the vertical telescope.

The plate-carrier C is fixed on two supports, which partici-

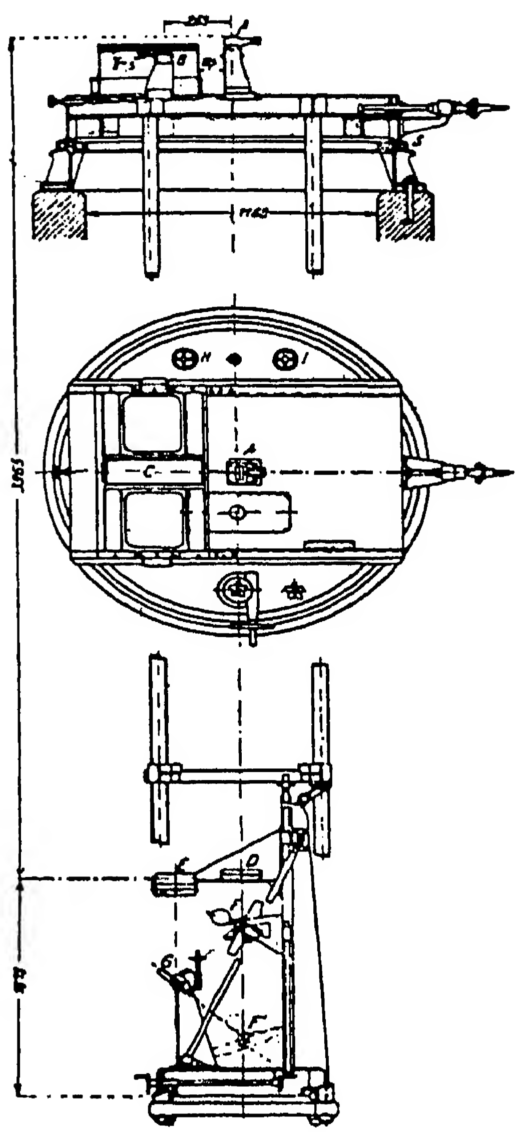

FIG. 20. Spectroheliograph and spectrograph of Arcetri solar tower. (Side elevation and plan view.)

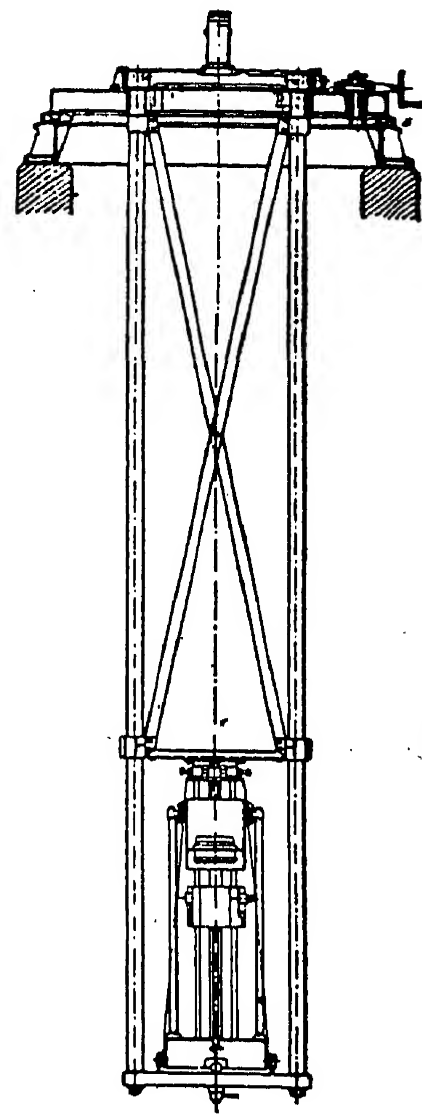

FIG. 21. Spectroheliograph and spectrograph of the Arcetri solar tower. (View from rear.)

pate in the motion of the platform on its vertical axle but not in the motion of the two slits and of the frame or lattice-work which supports its dispersive device, viz. the diffraction grating. At the lower end of this frame are mounted the two objectives D and E, each of 150 mm aperture and 4 m focal length, the mirror F and the diffraction grating G. The sun's image is made to fall on the first slit A, so that a beam of

parallel rays is cast on mirror F and thereby reflected on to grating G. The latter passes on the dispersed beam to the objective E, which produces an image of the spectrum on the photographic plate, the latter being almost in contact with the second slit. The second slit in front of the plate isolates any desired line of the spectrum, and by moving the spectroheliograph in front of the solar image (which is kept in a fixed position on the first slit by the clockwork mechanism) we obtain a photograph of the solar image in

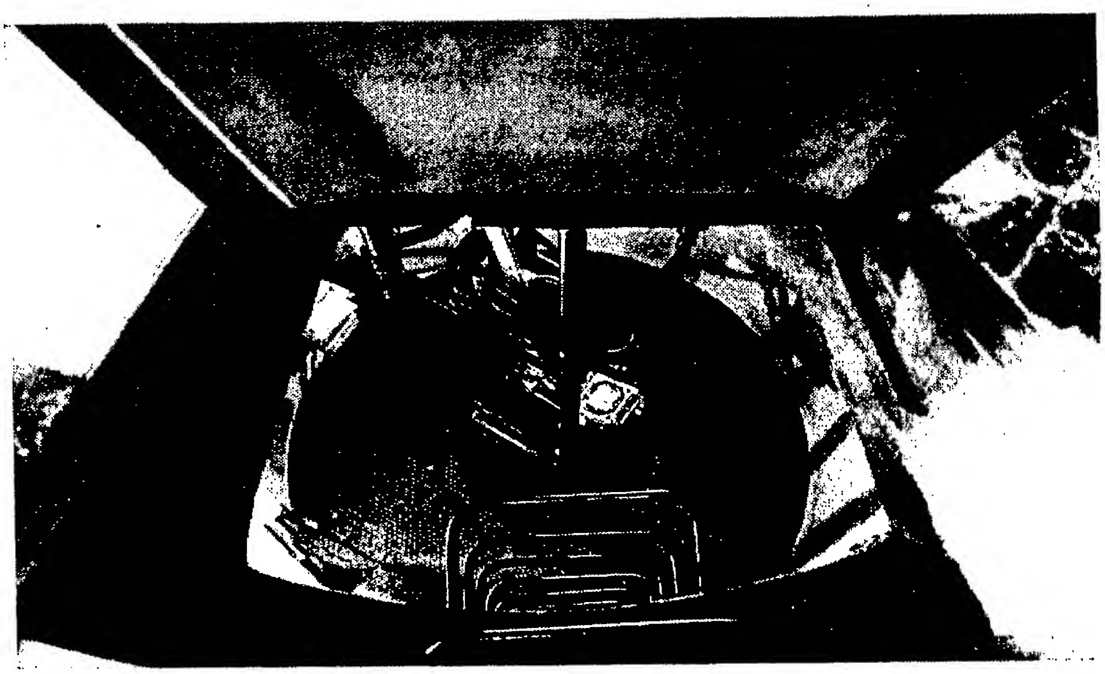

FIG 22. Interior of pit of Arcetri tower with lower part of spectrograph and spectroheliograph.
(Vertical view from above.)

the light of that given line. The mirror F can be shifted up to F′, and since in this way we vary the angle of incidence of the beam of rays on the grating, the dispersion is also varied within certain limits.

The required motion for the spectroheliograph is furnished by a small electric motor fixed to the wall of the observation room, transmission being effected by means of bevel gearing which enables the spectroheliograph to be rotated about its vertical axis around the east and west direction through an angle of $\pm 30°$, so that at all seasons the slit may always be perpendicular to the sun's equator.

Directly coupled to the axle of the motor is a tachymeter

on whose quadrant can be read the rate of motion applied to the spectroheliograph, which may vary from 0 to 25 mm per minute according to the gear used and the speed of the motor, so that different exposure-times may be selected.

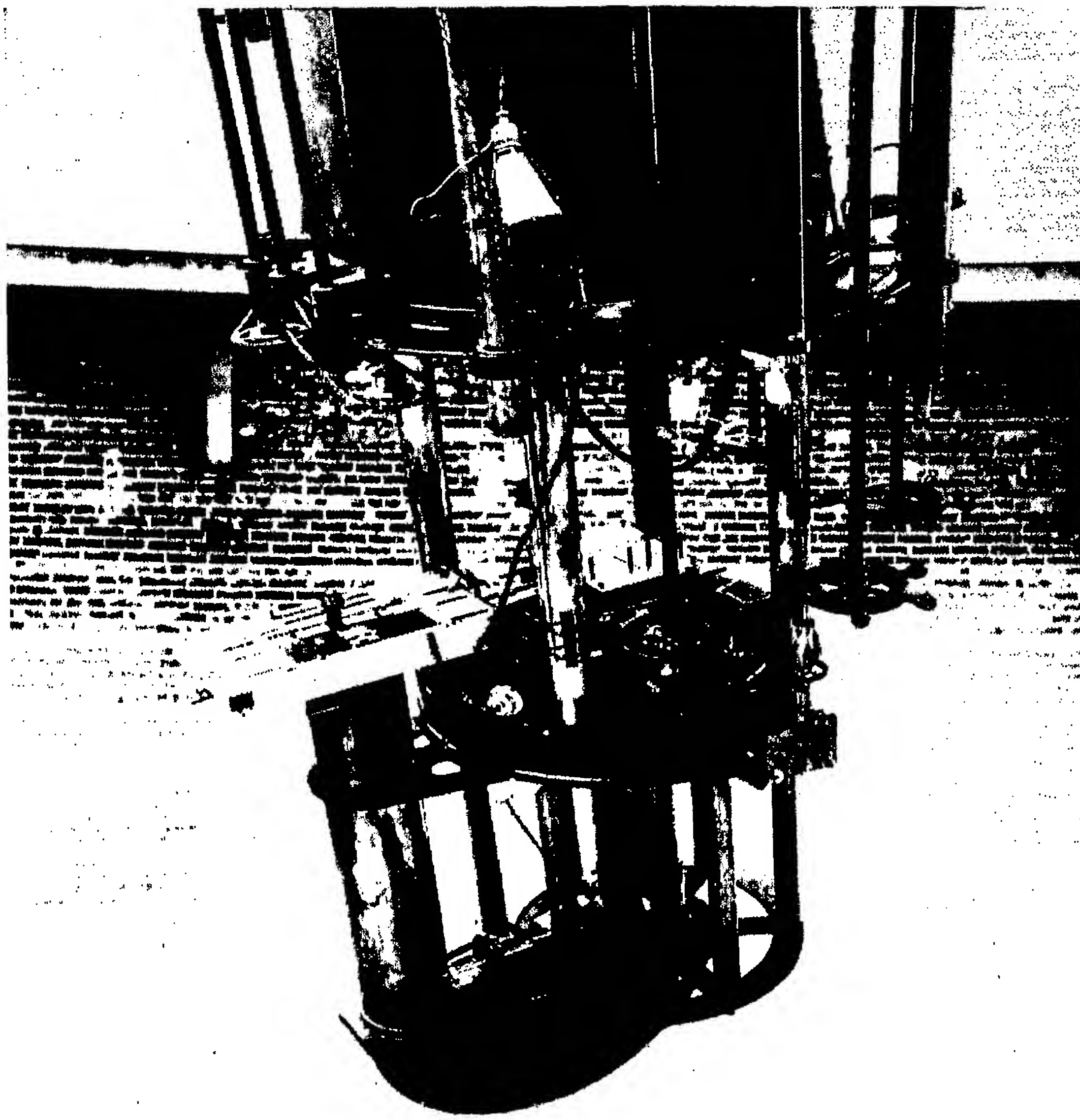

FIG. 23. The Rumford spectroheliograph fitted to the 40-inch refractor of the Yerkes Observatory.

A column fitted to the ceiling of the observation room supports an electric arc whose light is reflected in the interior of a spectrograph in order to obtain a comparison spectrum of a terrestrial source to be compared with that of the sun (Fig. 14).

The same instrument may, if desired, be used as a spectrograph (an instrument suitable for photographing a region of the spectrum) by simply detaching the support C (Fig. 20) of the photographic plate and the second slit B, and substituting for it another support bearing a frame for a photographic plate of the dimensions 9 × 36 cm on which a region of the spectrum of a length of 36 cm is projected. We thus change over in a few seconds from one instrument to the other, and in both there is a focal distance of 4 m, with a mean dispersion on the plates of 1 mm = about 4 angstroms.

The second type is exemplified by the Rumford spectroheliograph, which is fitted to the equatorial of the 40-inch refractor used at the Yerkes Observatory. In this instrument a uniform motion in right ascension imparted to the telescope causes the sun's image to traverse the first slit, and at the same time the photographic plate is made to move across the second slit, the necessary motion being furnished by small electric motors of a special type.

The light from the first slit, after having passed through the collimator, impinges on a mirror and is reflected by the latter into two prisms so as to produce a total deflection of the rays of 180° when the prisms are set to minimum deviation for the line under examination. When greater dispersion is required the mirror is replaced by a grating.

The necessity for large dispersion becomes manifest when the dark lines of the solar spectrum are used (except the two broad lines or bands H and K due to ionized calcium at the violet end); as these lines appear dark only by contrast with the luminous photosphere, but actually do emit light, it is possible by means of the spectroheliograph to obtain with them monochromatic images of the sun. But since these images may represent the gas or vapour which gives rise to a certain line, it is absolutely necessary that the dispersion be sufficient to render the spectral line broader than the second slit of the spectroheliograph; otherwise the light of the continuous spectrum on either side of the dark line will affect the plate.

At the astrophysical Observatory of Meudon near Paris, similar instruments for studying the monochromatic radiations of the sun were constructed by Deslandres almost contemporaneously with Hale. He commenced by taking photographs

of the sun with the second slit enlarged in such a way as to obtain a small portion of the solar spectrum on both sides of the line under examination, so that if the line is shifted owing to movements of vapour in the line of sight (Doppler effect) or through other causes, these displacements are recorded on the photographs. Such representations of the line are obtained for the whole solar disc by dividing it up into many sections

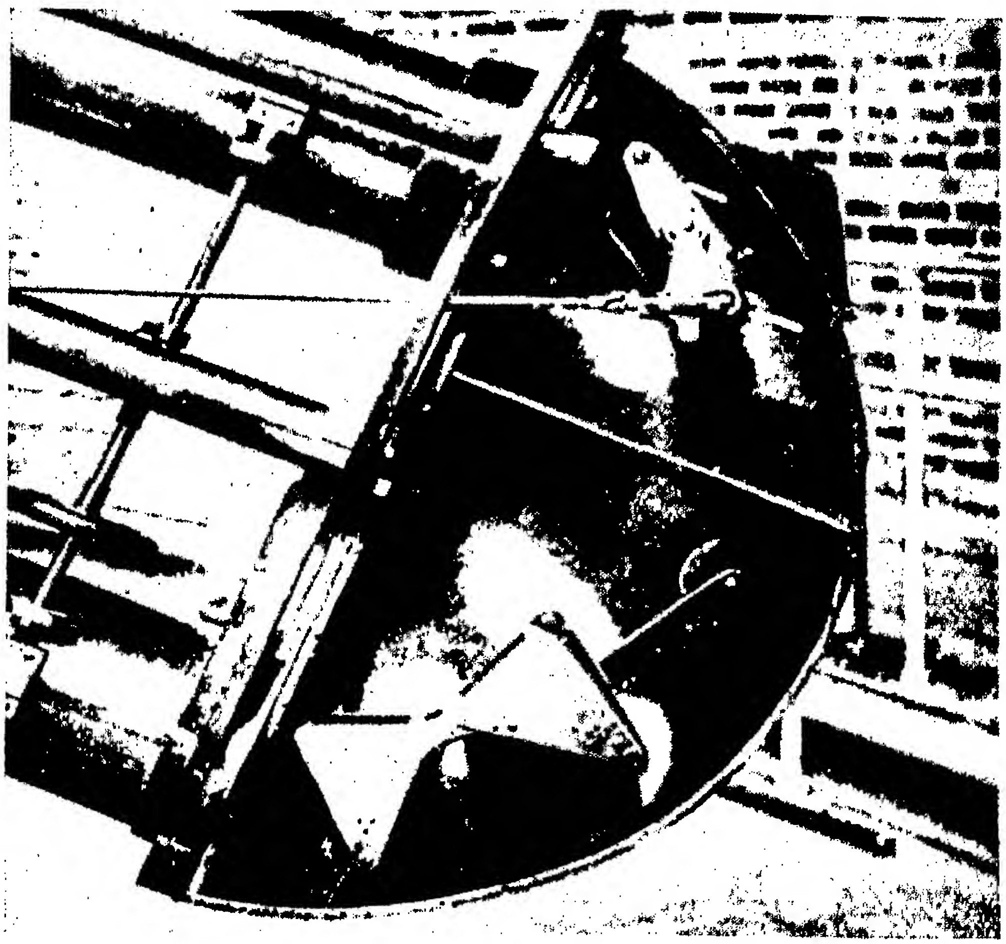

FIG. 24. Prism and grating box of the Rumford spectroheliograph.

and photographing it successively with a discontinuous movement of the spectrograph. Commencing with such an instrument, termed by Deslandres the *spectro-enregistreur des vitesses*, he readily changed over to the spectroheliograph, which is nowadays used at Meudon in conjunction with a horizontal telescope that may be used with numerous combinations of slits, a grating or prisms.

This spectroheliograph is of the second type, simultaneous movement of the object-glass (of 25 mm aperture and 4 m focal length) and of the photographic plate being furnished

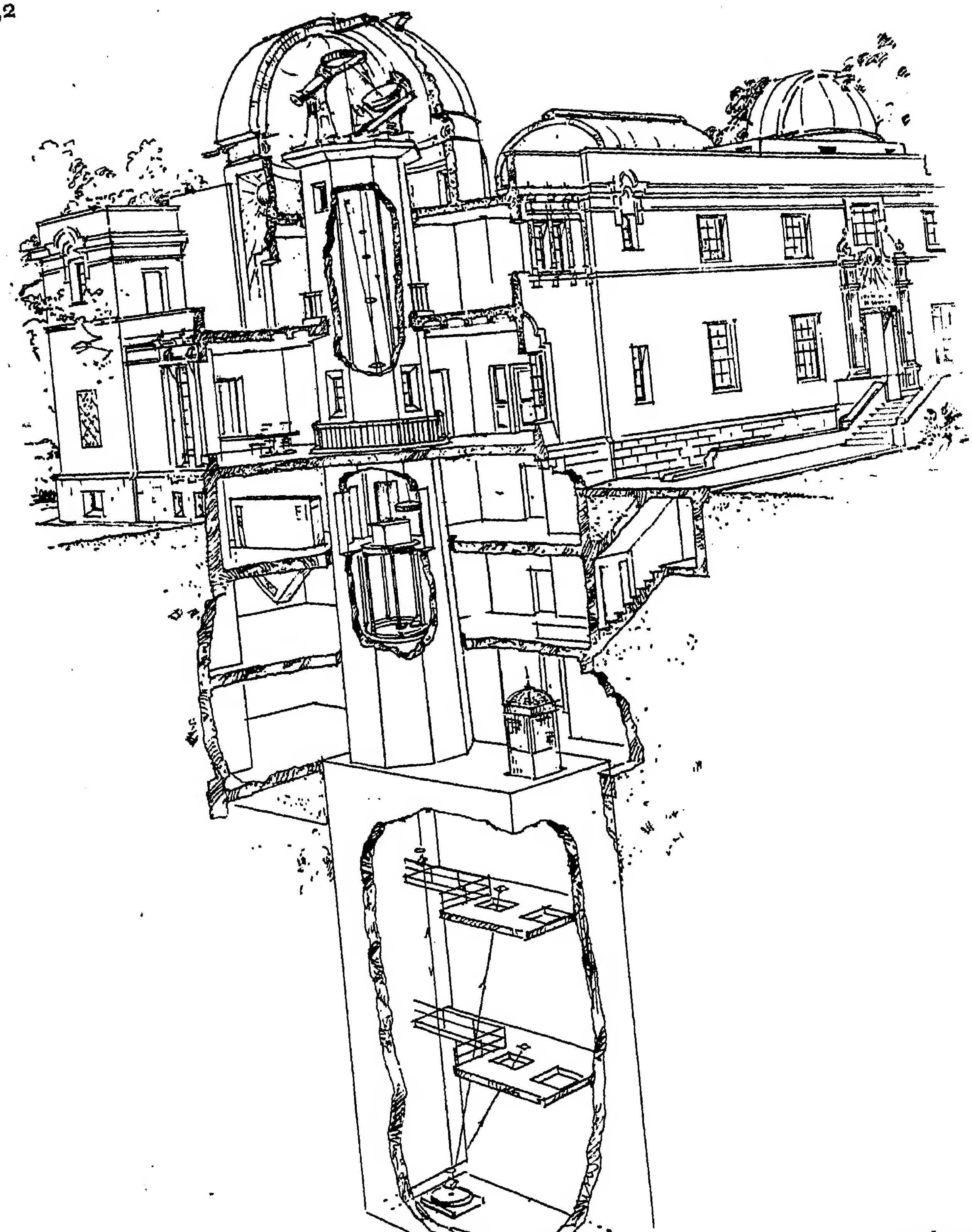

FIG. 25. Astrophysical laboratory with solar tower of the Technological Institute of Pasadena (California).

by two synchronized electric motors. The instrument described as "multiple" comprises four different combinations united around the same object-glass and the same collimator. The

purpose of these is to permit of obtaining solar images of varying sizes and varying dispersion in any line, by rapidly varying the optical parts and the dispersing device.

Photographic observation has made great strides and has hitherto been the only available means of studying monochromatic images, but visual observation also has its merit, for instance rapidity of observation, delicacy of the details

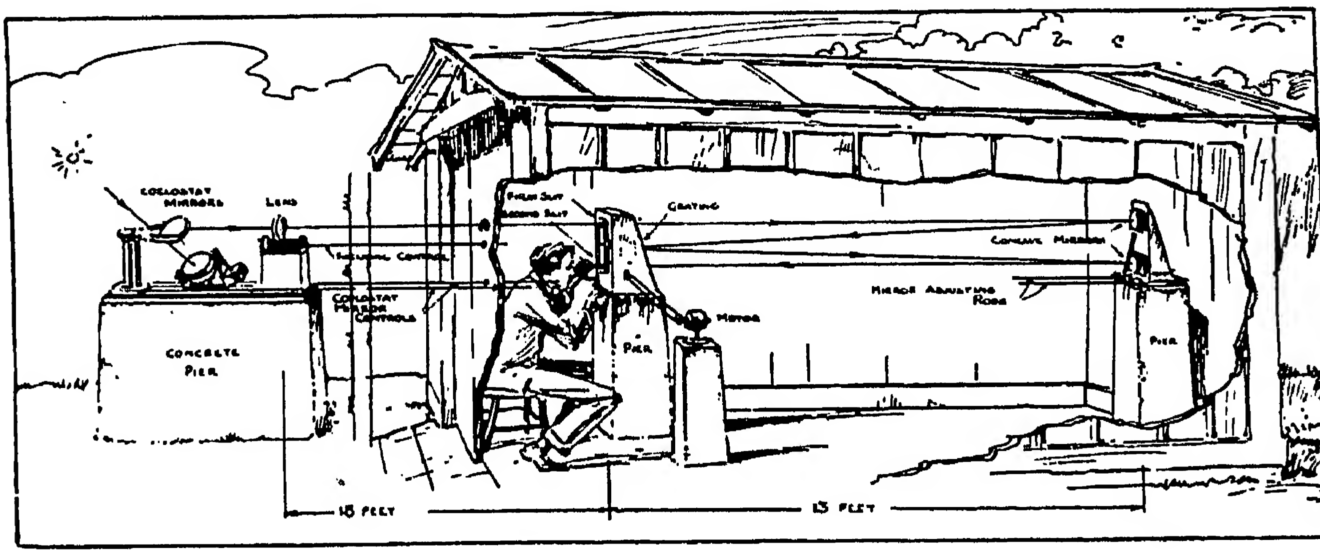

FIG. 26. Horizontal telescope and spectrohelioscope invented by Hale.

observed, and other features which are undeniable advantages. Visual observations of prominences on the solar limb are therefore still undertaken, and recently Hale, following up suggestions made by Janssen, Lockyer and Young, constructed a "spectrohelioscope" expressly for visual observation of solar phenomena in monochromatic light. The suggestion was to make the slit of the spectroscope oscillate or rotate so as to render the forms of the prominences visible, but in later developments the open slit was adopted, which we will deal with here.

It occurred to Hale to apply the oscillating slit to the spectroheliograph by making both the first and the second slit oscillate synchronously and by setting the latter to one of the lines of the spectrum, say the $H\alpha$ line of hydrogen, in order to obtain by persistence of vision a good view not only of prominences but also of dark and bright flocculi projected on the disc.

This idea has been embodied by Hale in his solar observatory at Pasadena in California, where the horizontal tele-

scope and a spectroheliograph are of the type already described.

The two slits of the spectroheliograph are at the ends of a horizontal bar which usually oscillates through a space of nearly half a centimetre, about a support midway between them. Since the optical parts are so arranged that the second slit constantly bisects the spectral line under examination when the two slits oscillate synchronously, we have a monochromatic aperture half a centimetre in width through which a given region of the sun can be examined with a suitable eye-piece giving an enlargement of two or three diameters. One merely has to adjust the speed of the motor supplying the horizontal oscillating motion so as to obtain a persistent image.

The delicate structure of the solar details which are thus made visible, and the feasibility of making observations in the various parts (violet or red) of one and the same line, enable the spectrohelioscope to be used as a guide to the spectroheliograph.

CHAPTER II

WHAT IS SEEN ON THE SUN BY DIRECT VISUAL AND PHOTOGRAPHIC OBSERVATION

Brightness of the Sun

The sun is simply one of the stars, but since it is very much closer to the earth than any other star it appears very much brighter than any other. As is well known, the magnitudes of the stars are described by a scale which was adopted by the ancients, in which the brightest stars were grouped in the first magnitude, and the faintest stars visible to the naked eye were said to be of the sixth magnitude. This scale has subsequently been extended to stars so faint that they can only be seen with a telescope. It has been found by observation that a difference of one magnitude corresponds to a ratio of light intensity of about 2·5. To use this same scale to express the intensity of the sun's light we have to use a negative number, which has been found to be − 26·72. On the same scale Sirius also has a negative apparent magnitude (− 1·6). The sun accordingly appears to be 2·5 raised to the power of (26·7 − 1·6) or about eleven billion times as bright as Sirius. But this great difference in brightness depends for the most part on the distances of the sun and of Sirius respectively from the earth, so that the sun, supposing it to be placed at the same distance from us as Sirius, would become twenty-seven times less luminous than Sirius and would appear to us as a star of the second magnitude, viz. 3·6 magnitudes fainter than Sirius.

When the sun is observed with a telescope by the methods indicated, we see a disc that is brightest at the centre and which gradually diminishes in brightness towards the limbs; this luminous surface is called the "photosphere." As a matter of fact the smoothness of the sun's surface is frequently marred by the presence of dark spots, whilst at the edges, over more or less extensive regions, there are streaks of intense brightness (brighter than the photosphere) to which has been given the name "faculae."

The photosphere is not white and perfectly even, but shows a kind of granulation which can be seen more clearly when the sun is caused to move at a certain speed in the field of the telescope, or on the screen during observation by projection. It can also be detected in photographs when taken

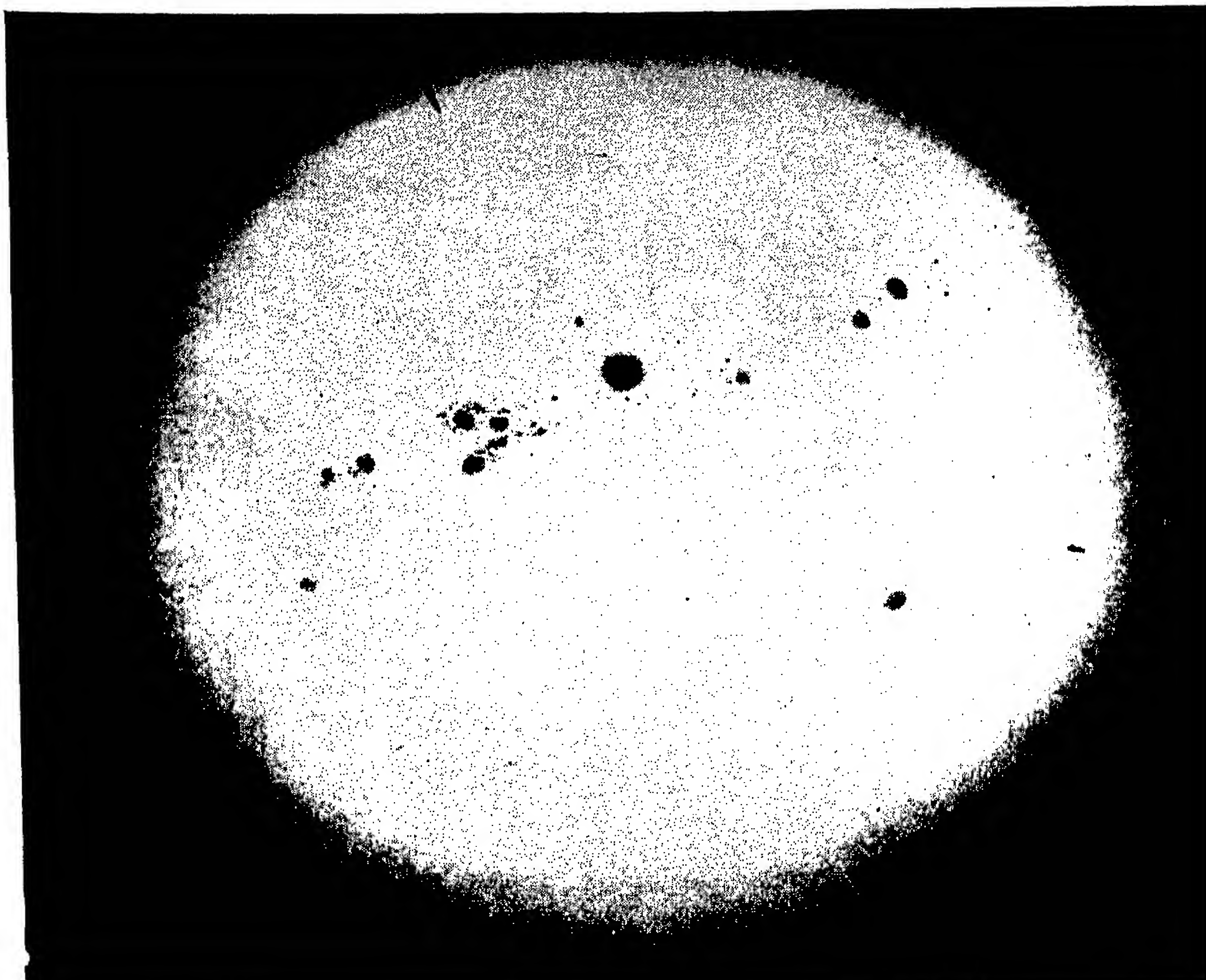

FIG. 27. The sun, photographed at Mount Wilson on November 30, 1929.

under ideal atmospheric conditions. The general aspect of the granulation is that of a large number of nuclei or "rice grains" which are delineated on a dark background; it is essentially these nuclei which give the photosphere its brightness. The nuclei stand out in very pronounced contrast to the background which, though intensely bright in itself, is relatively dark in comparison with the nuclei. The granulation is well

observed in the centre of the sun's disc; towards the edge, where the emerging rays lose much of their light because of their inclination to the sun's surface, the brightness of the nuclei decreases rapidly with respect to the background according as the all-round brightness decreases.

As a rule nuclei are circular in shape, but in the neighbour-

Fig. 28.—Granulation of the solar photosphere photographed at the Zô-sè Observatory, September 24, 1907.

hood of sunspots they assume an elongated form with a diameter that remains below one second of arc. Hence the granulation is variable and depends so much on atmospheric conditions that a study of its variations and especially of the motion of the nuclei, either visually or photographically, is very difficult.

Photographs of the sun taken under good atmospheric conditions show what Janssen described as the "photospheric network," because the photosphere does not appear uniform over

its entire surface, but shows a more or less considerable number of detached granules. Whilst in the spaces between these granules the nuclei are of varying size but are still clearly and distinctly visible, in the interior of the granules themselves the nuclei are only partially visible and appear distorted, many of them disappearing altogether and giving place to streaks. The distorted nuclei are more or less round, but at times they assume polygonal shapes; the diameter of these groups varies considerably but is often greater than one minute of arc.

A fairly plausible explanation of this distortion is that the light-rays are subject to disturbances as they pass through the terrestrial atmosphere. The solar limb is always seen as sinuous in outline, owing to the continual changes in the layers of the terrestrial atmosphere; hence the same disturbances which affect the light of the edge of the sun must also affect the rays for the whole of the sun's surface.

The varying relative brightness of the brighter and darker portions of the photosphere may be due to different intensities of gas condensation occurring in the photosphere, and to actual columns of ascending and descending vapours.

In the normal granulation we often find regions of the sun's disc on which no nuclei are visible and the appearance is that of small dark specks possessing the same luminosity as their background. When these specks increase in size they gradually become darker until they appear entirely black against the bright background of the photosphere. These dark specks, termed "pores," are nothing more than very small sunspots.

Sunspots

When the pores on the sun increase considerably in size they are called "spots." The origin and peculiar development of a sunspot may be described as follows on the basis of observation.

Several small pores or spots generally coalesce and form two large spots; the preceding spot or leader (in the direction of the sun's rotation), viz. the one that will arrive first at the eastern limb, is as a rule the more compact of the two and has a faster longitudinal motion. Gradually a bridge of smaller

spots unites the two spots; the bridge, however, soon disappears and with it the following spot. The one remaining, i.e. the leader, then assumes a circular shape, becomes smaller and smaller, and finally dissolves into a number of small spots and pores from which fresh sunspots are frequently reproduced.

Both the duration and size of the spots are very variable. Sometimes the phenomenon is completed in a few days, but it often lasts for months, viz. throughout several successive solar rotations.

The majority of the pores are not transformed into spots, and there are spots whose diameter many times exceeds that of the earth. The pores or small spots or those of medium size are usually round. The larger spots, on the other hand, are generally of exceedingly complicated shapes and often occur in groups comprising a large number of smaller spots and pores

Each completely developed spot consists of two parts: the *umbra* (the inner part, seen as a uniformly dark surface) and the *penumbra*, which surrounds the umbra. Pores appear to have no penumbra or at any rate only a very faint one. In the neighbourhood of the spots the granulation differs from that in other places on the sun's surface, it is very dense and the nuclei are larger and packed more closely together, so that in several places the darker background is often completely hidden and the granulation can hardly be distinguished. The contrast between the bright photosphere and the penumbra is most marked. The background of the penumbra becomes very dark, the nuclei assume an elongated form and are grouped together radially towards the centre of the spot with comparatively large intervals in between, to end as abruptly as they began. In the centre is the uniformly dark umbra, which, however, is only dark by reason of its great contrast with the photosphere, for in reality it is extremely brilliant.

Galileo had already noted this in his first letter to Marcus Welser questioning Father Scheiner's observations: "*Rather I judge the spots seen in the sun to be not only less dark than the dark patches seen in the moon, but to be no less bright than the brightest parts of the moon when fully illuminated by the sun.*" This may be easily observed when one of the inner planets, Venus or Mercury, passes across the sun's disc. The planet's disc presented to the earth is entirely dark, but its apparent brightness

is due to our atmosphere being illuminated by the sun's rays and returning reflected light to the planet. For this reason the apparent brightness of the planet is considerable, but compared with the planet the umbra of a sunspot is much brighter,

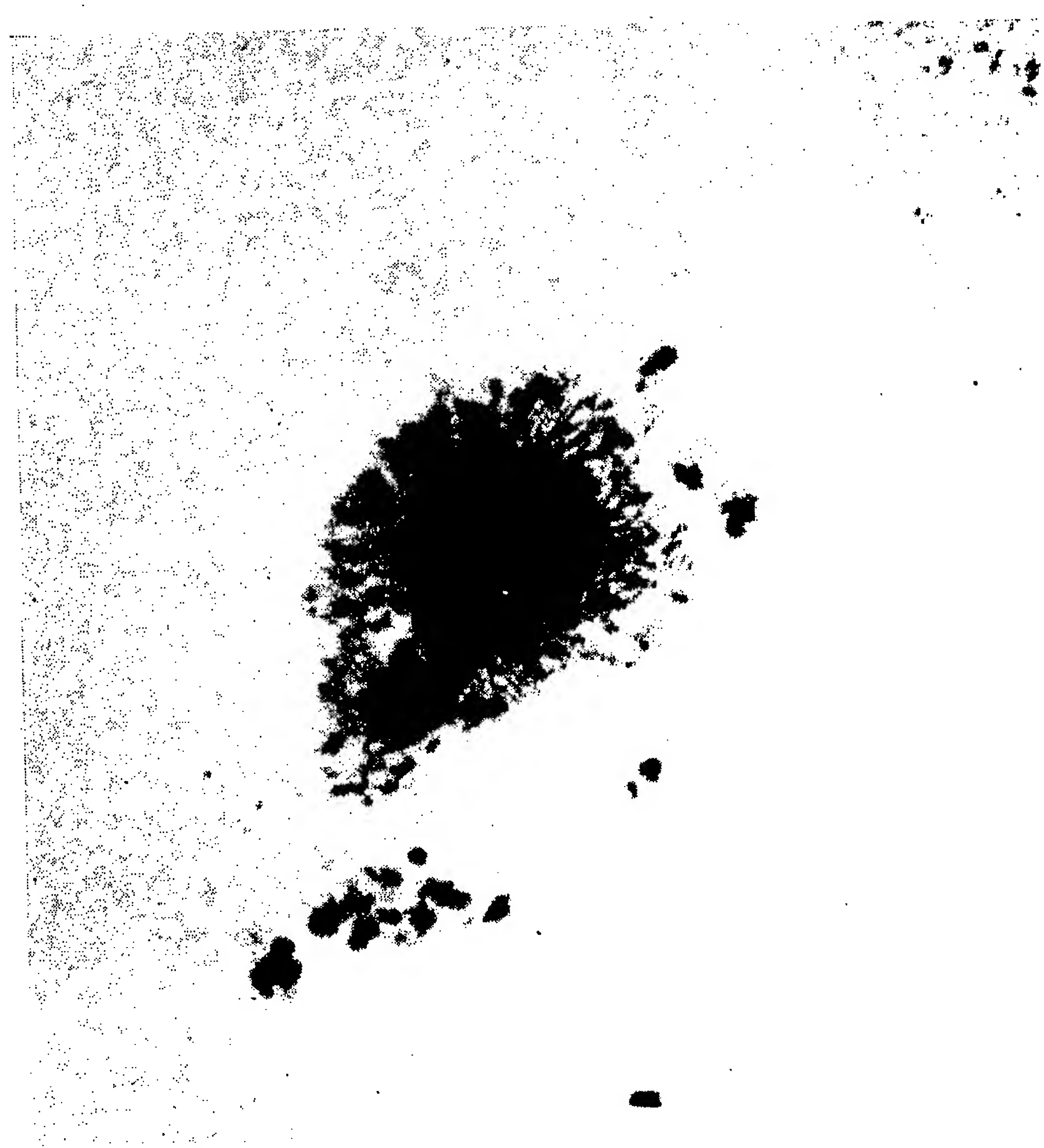

Fig. 29. Large sunspot photographed at the Yerkes Observatory, June 30, 1928.

and added to the light of the umbra there is also the light reflected from the terrestrial atmosphere. The numerous estimates of the brightness of the umbra vary considerably and fluctuate between 1/10 and 1/50 of the brightness of the photosphere.

The spots, which split up into two or more parts, present

even in their interior a very brilliant mass which divides part of the umbra in like manner to a bridge (see Fig. 29); in large spots these bridges are rather frequent; we shall see later how this can be accounted for by the results of spectroheliographic observation.

During periods of great solar activity we can observe spots of very large size, in fact a nucleus of over 2′ has been measured; this represents a diameter of about 90,000 km,

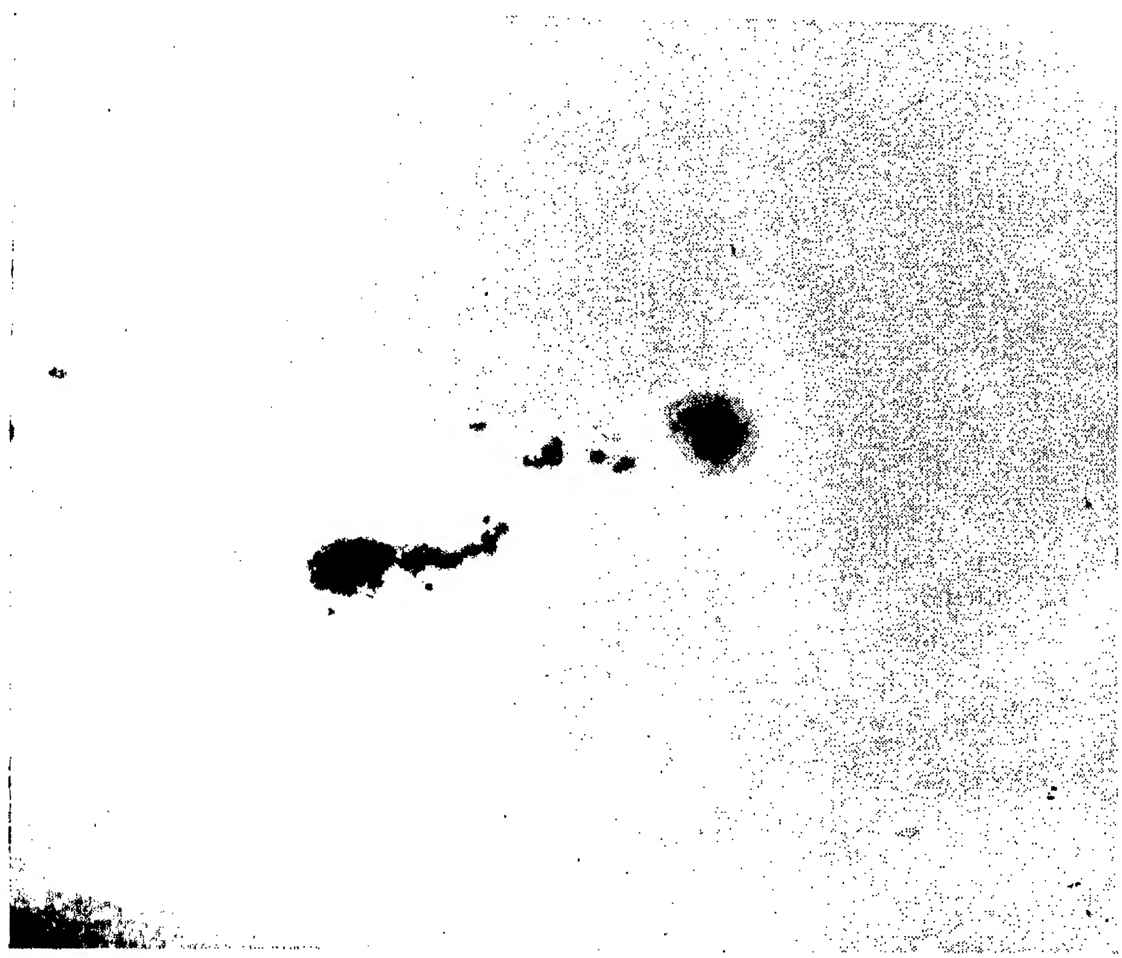

FIG. 30. Group of sunspots photographed at the Yerkes Observatory.

about seven times that of the earth. Such huge sizes are, however, comparatively rare; sunspots with a total diameter (including the penumbra) of 50,000 km are exceptional occurrences. The largest spot on record would seem to be that which appeared in 1858; it was 230,000 km across, viz. about 18 times the earth's diameter.

A spot whose diameter attains 40,000 km is visible to the naked eye, and numbers of them are to be observed during the periods of maximum activity. In order to form an idea

of the true shape of sunspots it must be remembered that they are on a sphere and consequently appear in different perspectives according as we see them close to or far from the solar limb. Moreover, since the spots are presumably cracks in the solar photosphere, they will develop not only on the surface but also towards the interior or exterior of the sun, and hence the problem resolves itself into determining their form and level on the surface of the photosphere.

A. Wilson of Glasgow was the first to ascertain by direct observation, in 1774, that a sunspot having an umbra and penumbra of circular and concentric formation when situated at the centre of the sun, seemed to undergo a systematic change of shape as it approached the limb. The umbra became smaller and smaller, and the eastern part of the penumbra also decreased in size, whilst the western part facing the limb also decreased, but at a much slower rate. Near the edge of the limb the umbra disappeared completely, and a fine streak was all that could be seen of the western portion of the penumbra; the whole spot was reduced to a dark line. On the reappearance of the spot at the sun's eastern limb, thirteen days later, the whole phenomenon was repeated in the reverse order as the spot moved from the eastern limb to the centre. The simple conclusion which Wilson quickly arrived at was that sunspots are funnel-shaped and situated with their central part at a lower level than the photosphere.

This level, the depth of the spot, may be determined by measuring the width of the penumbra when the spot is near the centre of the disc, and also the angle between the centre of the disc and the umbra of the spot when the eastern penumbra disappears. Assuming that the shape of the spot and hence the width of the penumbra has remained sufficiently constant during the passage of the spot from the centre to the limb, it is easy to infer the depth of the spot.

Wilson thus found that this depth was equal to about one-third of the earth's radius. This result has since been confirmed by Herschel, Secchi, Tacchini, and P. Chevalier, although several spots have been observed which do not conform to Wilson's observations.

Warren de la Rue, discussing observations made at Kew, found that out of eighty-nine normal spots, seventy-two agreed

with Wilson's theory and seventeen did not. P. Chevalier after a long series of observations effected at Zô-Sè in China, concluded that the spots are generally depressions at various depths of the photosphere, but that on an average they are at a smaller depth than that found by Wilson, that is, 1″ or 750 km.

If, in the majority of cases, sunspots are actual cavities, then a depression more or less deep (depending on the size and depth of the spot) should be noticed when they are on the limb. This was indeed already noticed by Cassini in 1719 and later by other observers. Some spots, however, as already stated, do not follow the regular course observed by Wilson but show a reverse phenomenon, so that it cannot be laid down as a general rule that the umbra is at a lower level than the photosphere.

The hypothesis has been put forward that, although the umbra is a depression in the penumbra, the whole of the umbra is nevertheless at a higher level than the photosphere. We shall show later how the spectroscope enables these different levels to be determined with greater certainty.

Faculae

Faculae appear as streaks of intense brightness (generally of greater brightness than the photosphere) extending irregularly for many thousands of kilometres over the sun's surface. They are readily seen near the edge of the sun, where the photosphere is less bright; there they show up more vividly by contrast. Their form is ramified and they often change their shape, sometimes in a few hours, though they may remain for weeks in the same region of the sun. When they approach quite near to the limb it sometimes seems as if they emanate from it, as if they were elevations of the photosphere. If the faculae are indeed at a higher level than the photosphere, this at once explains why they appear so brilliant in the vicinity of the solar limb. As a matter of fact the diminution of brightness of the photosphere at the limb is probably due to the presence of a solar atmosphere whose absorbing power must increase considerably towards the sun's surface as a result of the increasing density.

When a celestial body is surrounded by an atmosphere of

definite thickness it is obvious that the rays emerging perpendicularly to the surface of that body traverse a thinner layer of its atmosphere than the rays emerging tangentially to its surface. Hence the light that reaches us from the limbs traverses a highly absorptive layer of atmosphere and therefore appears less bright than at the centre of the sun's disc.

We shall see later how this remarkable absorption is variable in the different wavelengths of solar radiations. If faculae rise above the photosphere, the light they emit will have traversed a less high and less dense layer and consequently they will lose but little of their brightness, whereas rays emanating from the lower layers of the photosphere undergo more intense absorption.

Whilst faculae are chiefly observed around the regions occupied by sunspots, they are not confined to these regions but are also found in regions completely free from spots.

Distribution of Sunspots and Faculae and their Periodicity

In order to study the distribution of sunspots and faculae on the solar globe it is necessary to determine the co-ordinates of these phenomena in the same way as is done for points on the earth.

The early observers had noticed that sunspots and faculae move from east to west in circles parallel to the solar equator, and that when they develop on the invisible hemisphere they make their appearance on the eastern limb, to disappear on the western. When these phenomena are of fairly long duration they are manifested during a complete rotation or during several rotations of the sun. From the nature of their movements it has been concluded that the sun rotates in a period of twenty-seven terrestrial days.

The points at which the theoretical axis of solar rotation cuts the surface of the sphere are the sun's poles: the north pole is the one which, seen from the earth, is directed towards the north of the celestial sphere, the other is the south pole. As on the earth, every plane through which the sun's axis passes is a meridian plane. Any meridian which, at a given moment, divides the visible disc of the sun in two can be selected as the meridian of origin or zero meridian, from

which are reckoned, east and west, the *heliographic longitudes* which are analogous to the geographical longitudes of the earth. As there are no points of reference on the sun, we must select a new zero meridian for each series of observations. Now if we imagine planes traced at right angles to the sun's axis, these planes will divide the sphere into so many small circles representing the *parallels* or circles of latitude. The great circle traced out by the plane perpendicular to the sun's axis and passing through the sun's centre, is called the *solar equator*, and from it are reckoned, north and south, the heliographic latitudes which are analogous to the geographical latitudes of the earth.

The sun's equator forms an angle of about 7° with the ecliptic or plane of the earth's orbit, and the terrestrial equator is inclined to the ecliptic at an angle of 23·5°. Owing to this inclination of the sun's equator to the ecliptic and hence to the line of sight earth-sun, the spots do not as a rule move across the disc in straight lines, but describe ellipses representing the orthographic projection of the solar parallels as seen from the earth. Only when the earth is at the two opposite points of its orbit at which the ecliptic cuts the plane of the solar equator, does the motion of the sunspots appear to be in straight lines, since in that case the solar equator is a diameter of the apparent disc.

At the two positions mentioned, the earth being situated in the plane of the solar equator, the line of sight earth-sun is at right angles to the sun's axis of rotation, which will therefore be in the plane perpendicular to the line of sight, viz. in the plane of the apparent disc. At all other positions of the earth in its orbit, the sun's axis appears more or less inclined to the plane of the apparent disc, from a minimum of 0° to a maximum of 7°. This inclination is equal to the angle which the solar radius directed towards the earth forms with the solar equator, and may therefore be termed the heliographic latitude of the earth. Obviously this angle will not suffice for determining the position of the axis as seen from the earth, for we must also know its position angle, viz. the angle which the projection of the axis on the apparent disc forms with a predetermined direction. Now the apparent diurnal motion of the sun in the heavens is in the direction east-west, so that

by noting the line of displacement of a well-defined point on the sun's disc we can obtain the direction north-south which is at right angles to it, this direction being established in the heavens by the celestial meridians, and to it we refer the position angle of the axis of solar rotation, which may vary from 0° to 26° 25'.

The aforesaid inclination and the position angle now determined depend not only on the position of the earth in its orbit but also on the inclination of the solar equator to the plane of the ecliptic or on the earth's inclination to that plane. We have already stated that during the two epochs at which the earth traverses the plane of the sun's equator, which epochs occur early in June and early in December, the solar axis is in the plane of the apparent disc and the two poles are on the actual edge of the limb. Under these conditions the position angle of the axis is a maximum and is exactly equal to 26° 25', which is identical with the angle of inclination of the solar equator to the terrestrial equator, whilst the inclination to the solar disc is nil. Moreover, during the two epochs of the year at which the position angle of the solar axis is nil and its projection coincides with the direction north-south (at the beginning of January and beginning of July), the inclination to the apparent disc attains its maximum value, which is 7°, corresponding exactly to the inclination of the solar equator on the ecliptic.

From June to December the north pole of the sun is, with respect to the apparent disc, turned towards the earth, whilst from December to June the sun's south pole is directed towards the earth. From January to July the north pole is at the west of the direction north-south and from July to January at the east thereof.

The *Nautical Almanac*, the *American Ephemeris*, and the *Handbook of the British Astronomical Association* publish annually an ephemeris for physical observations of the sun, giving us for each day not only the two data relating to the axis, i.e. the position angle and the inclination of the solar axis (or heliographic latitude of the centre of the sun's disc), but also the heliographic longitude of the centre of the disc (reckoned from the solar meridian), which was traversed by the ascending mode of the solar equator on the ecliptic on January 1, 1854.

We have already stated that the average time taken by a sunspot to return to the same position of the disc with respect to us is twenty-seven days. This interval is not the real period of solar rotation but the period of *synodic rotation*, as it is termed, because the earth moves forward a certain distance in its orbit during the interval of a solar rotation. In order to obtain the real (or *sidereal*) rotation from the synodic rotation we must correct the latter by counting the time the earth travels over the section of path it traverses during the period of a synodic rotation.

Since the spots are not fixed points on the solar surface but often have a proper motion, it is obvious that we cannot deduce from them a very accurate value for solar rotation, as would be possible, for instance, by the spectroscopic method. Moreover, we shall see that the sun rotates at different speeds in the different latitudes; however, the mean value of sidereal rotation may be taken to be that obtaining at the solar equator, viz. 25·35 days.

The position of the solar equator in space is determined with reference to the plane of the ecliptic, by means of two elements: the *inclination*, which is simply the angle formed by the two planes, and the *longitude of the node*, being the angle between the straight line of intersection of the two planes and a predetermined direction of reference on the ecliptic. The nodes are the two points at which the solar equator cuts the plane of the ecliptic, the *ascending node* being the one at which an equatorial point on the sun traverses the ecliptic as a result of solar rotation; the other node is referred to as the *descending node*. The *longitude of the node* is always understood to mean that of the *ascending node*.

The problem of determining these two elements has been solved by several observers, beginning with Father Scheiner, and the values nowadays adopted are respectively 7° 15′ for the inclination of the solar equator on the ecliptic and 73° 40′ for the *longitude of the node* in 1850; the indication of epoch for the second value is necessary because this value is not constant but increases annually by about 0·8′ on account of precession and is at present nearly 75°.

On the other hand, when these elements are known, the co-ordinates of a spot or of any other phenomenon happening

in the sun may be deduced by simple formulae of spherical trigonometry, their position being referred either visually or photographically, by means of the limbs, to the centre of the sun's disc.

The systematic observation of the spots and the determination of their position on the sun prove that they do not originate haphazard over the whole solar surface, nor always with the same frequency. As a matter of fact there are epochs at which the sun is completely free from spots and other epochs at which there are a very large number, the spots being confined to two zones of solar latitude, viz. between 5° and 40° north or south of the solar equator. They rarely appear on the solar equator and have never been observed at a latitude greater than 45°. Moreover, it has been found that their mean latitude at a given epoch is closely related to their frequency. By simply studying the number and size of the spots it is found that both these factors vary considerably with time, not only from day to day but also from month to month and from year to year. It had long been suspected that these variations were periodical in nature, but it was Schwabe who, as already stated, found that the return of maximum sunspot frequency occurs about every eleven years. The number of spots, though variable from day to day, shows a regular trend over a long period, with a maximum during which we can observe (counting both large and small ones) up to 25 or 30 per day, and a minimum during which not a single spot is to be seen on the sun for several days or weeks. R. Wolf succeeded in collecting sunspot observations made since the time of Galileo and in this way he established for their frequency a mean period of 11·1 years, that period being, however, subject to considerable fluctuations.

In order to calculate this variable frequency he counted the spots with his "relative numbers," which are still in use to-day. They comprise the number of groups of spots on the sun's surface on a given day and also the number of individual spots. Whilst each spot counts as one, each group counts as ten, and hence the relative number is the number of groups multiplied by ten plus the number of individual spots. Moreover, in order to consider and treat in conjunction with each other the observations made by several observers with instru-

ments of different powers, Wolf reduced them to the same basis by means of properly calculated factors, taking the factor

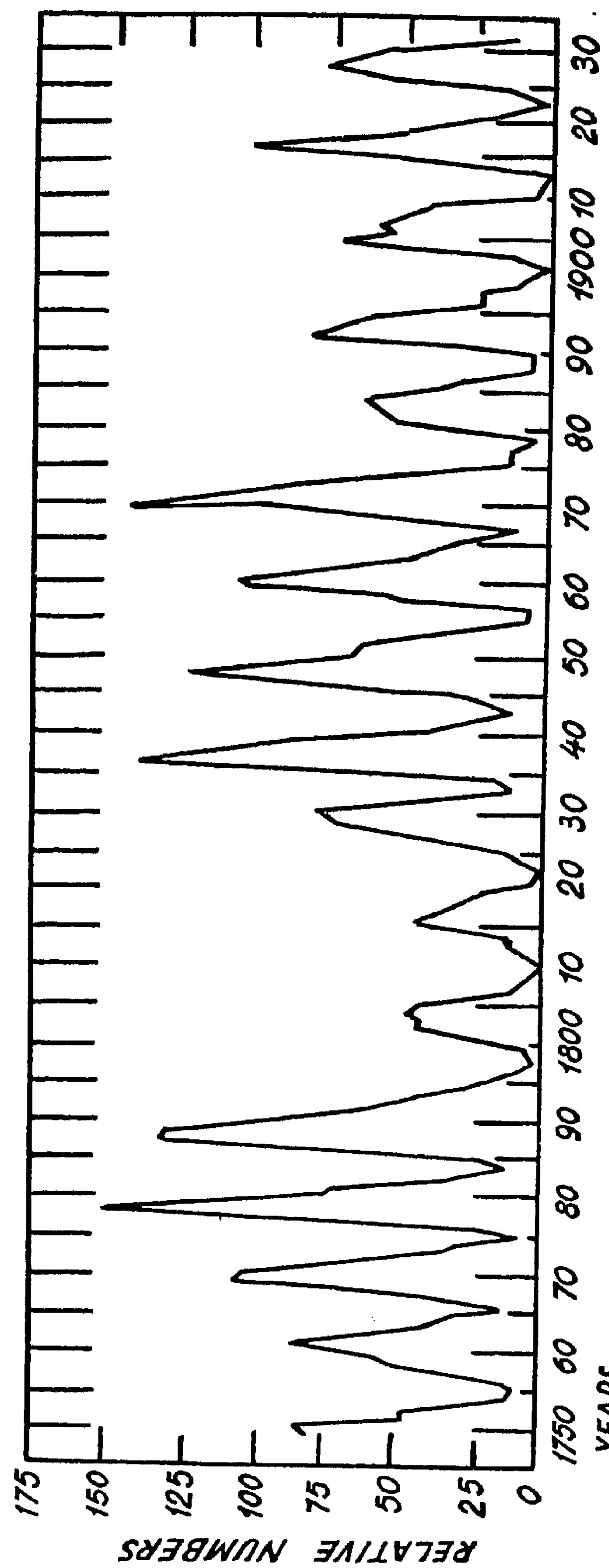

Fig. 31. Cycles of solar activity determined with Wolf's relative numbers from 1750 to 1930.

1 for his observations made at Zürich with a telescope of 10 cm aperture and an enlargement of 64.

Year	*R. N.*	*Year*	*R. N.*	*Year*	*R. N.*	*Year*	*R. N.*
1749	80·9	1796	16·0	1843	10·7	1890	7·1
1750	*83·4*	1797	6·4	1844	15·0	1891	35·6
1751	47·7	1798	4·1	1845	40·1	1892	73·0
1752	47·8	1799	6·8	1846	61·5	*1893*	*84·9*
1753	30·7	1800	14·5	1847	98·5	1894	78·0
1754	12·2	1801	34·0	*1848*	*124·3*	1895	64·0
1755	9·6	1802	45·0	1849	95·9	1896	41·8
1756	10·2	1803	43·1	1850	66·5	1897	26·2
1757	32·4	*1804*	*47·5*	1851	64·5	1898	26·7
1758	47·6	1805	42·2	1852	54·2	1899	12·1
1759	54·0	1806	21·1	1853	39·0	1900	9·5
1760	62·9	1807	10·1	1854	20·6	1901	2·7
1761	*85·9*	1808	8·1	1855	6·7	1902	5·0
1762	61·2	1809	2·5	1856	4·3	1903	24·4
1763	45·1	1810	0·0	1857	22·8	1904	42·0
1764	36·4	1811	1·4	1858	54·8	*1905*	*63·5*
1765	20·9	1812	5·0	1859	93·8	1906	53·8
1766	11·4	1813	12·2	*1860*	*95·7*	1907	62·0
1767	37·8	1814	13·9	1861	77·2	1908	48·5
1768	69·8	1815	35·4	1862	59·1	1909	43·9
1769	*106·1*	*1816*	*45·8*	1863	44·0	1910	18·6
1770	100·8	1817	41·4	1864	47·0	1911	5·7
1771	81·6	1818	30·4	1865	30·5	1912	3·6
1772	66·5	1819	23·9	1866	16·3	1913	1·4
1773	34·8	1820	15·7	1867	7·3	1914	9·6
1774	30·6	1821	6·6	1868	37·3	1915	47·4
1775	7·0	1822	4·0	1869	73·9	1916	57·1
1776	19·8	1823	1·8	*1870*	*139·1*	*1917*	*103·9*
1777	92·5	1824	8·5	1871	111·2	1918	80·6
1778	*154·4*	1825	16·6	1872	101·7	1919	63·6
1779	125·9	1826	36·3	1873	66·3	1920	37·6
1780	84·8	1827	49·7	1874	44·7	1921	26·1
1781	68·1	1828	62·5	1875	17·1	1922	14·2
1782	38·5	1829	67·0	1876	11·3	1923	5·8
1783	22·8	*1830*	*71·0*	1877	12·3	1924	16·7
1784	10·2	1831	47·8	1878	3·4	1925	44·3
1785	24·1	1832	27·5	1879	6·0	1926	63·9
1786	82·9	1833	8·5	1880	32·3	1927	69·0
1787	*132·0*	1834	13·2	1881	54·3	*1928*	*77·8*
1788	130·9	1835	56·9	1882	59·7	1929	65·0
1789	118·1	1836	121·5	*1883*	*63·7*	1930	35·7
1790	89·9	*1837*	*138·3*	1884	63·5	1931	21·2
1791	66·6	1838	103·2	1885	52·2	1932	11·1
1792	60·0	1839	85·8	1886	25·4	1933	5·7
1793	46·9	1840	63·2	1887	13·1	1934	8·7
1794	41·0	1841	36·8	1888	6·8	1935	36·1
1795	21·3	1842	24·2	1889	6·3	1936	80·4

The results obtained by Wolf have been published by him in the *Astronomische Mitteilungen* of the Zürich Observatory, where they were and are still being continued by his successors A. Wolfer and W. Brunner with international co-operation.

The Wolf numbers for each year, from 1749 to 1936, are given in the table opposite in view of their importance in solar physics and the relations between solar and terrestrial phenomena.

A more precise determination of solar activity due to the phenomenon of sunspots is obtained by measuring the total areas covered by the spots (umbra and penumbra), as is done systematically, for instance, at Greenwich Observatory. From daily photographs of the sun, by means of a grating engraved on glass and allowing for the effect of perspective, the area is measured which they occupy in millionths of the visible surface of the sun. Thus, for example, at the 1859 maximum it was found that the mean daily area was about 1400 millionths, whereas at the following minimum in 1867 the area covered was only 200 millionths. At the 1913 minimum the daily mean area for the umbrae was only one millionth, that of the complete spots (umbra and penumbra) 7, and that of faculae 95, whilst at the 1917 maximum the figure for the umbrae was 247, for the complete spots 1537 and for the faculae 2305.

The Wolf numbers for the same years are found in the foregoing table, from which can be deduced the deviations of the various periods from the average of 11·1 years. These deviations can also be clearly seen in the diagram, which gives a visual picture of the varying intensity of sunspot frequency from cycle to cycle; it appears that a group of cycles with high activity is followed by a group with low activity. Moreover, from this same diagram or rather from the upper part of Fig. 32, it is clear that the ascent from minimum to maximum is steeper than the descent from maximum to minimum, in fact it has been inferred from the average of the cycles observed hitherto that the time interval between a maximum and a minimum amounts to 6·0 years, whereas from a minimum to the next maximum the interval is only 5·2 years.

As we shall see, considerations based on the study of magnetic fields in sunspots lead us to suppose that the complete solar cycle has a duration of 22 or 23 years rather than of

11 years, and that the varying intensity of the cycles is due to superimposition of other shorter or longer periods in the period of 11 years. Schuster, discussing a series of cycles by harmonic analysis, computes at least four superimposed periods. These

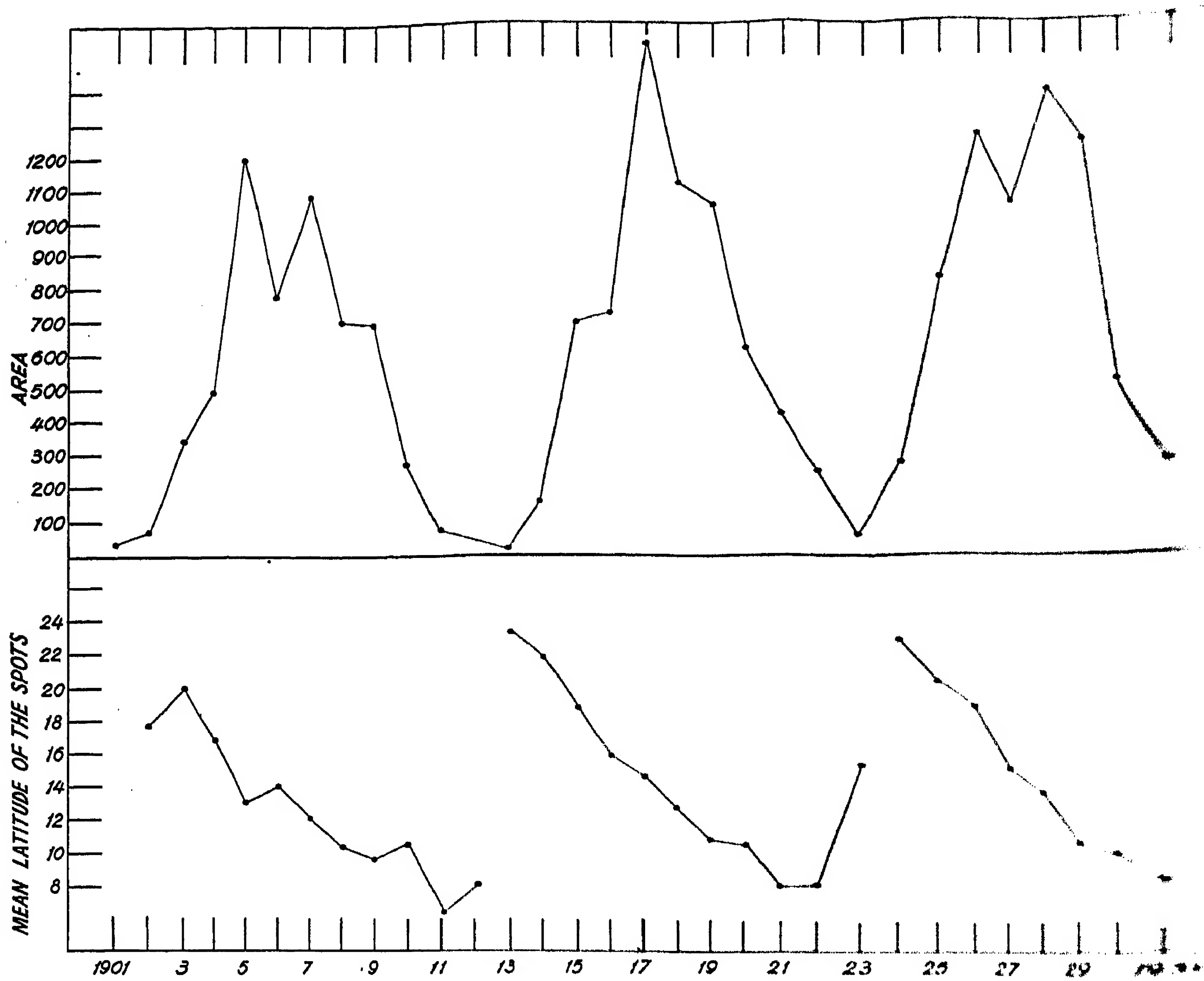

FIG. 32.

Above: The three cycles from 1901 to 1931.
Below: Shift in the mean latitude of sunspots during the three cycles.

do not, however, represent the observed fluctuations with sufficient accuracy. Oppenheim, by similar theoretical means, establishes two cycles: one of 11·25 years and a super-period of 450 years, with the combination of which he succeeds in representing Wolf's relative numbers fairly well.

We have already referred to the fact that sunspots, besides

varying their frequency with time, also change their latitude. Spörer was the first to investigate this phenomenon, which is of great theoretical importance in connection with the physical constitution of the sun and is also related to the magnetic period of the spots.

The regions of the solar surface in which spots occur, are situated in two belts in 30° north and south latitude, where they manifest themselves somewhat before the commencement of a given period (minimum activity). These belts, during progression of the cycle, drift towards the solar equator, while the spots decrease in number until they almost die out, after six or seven years, towards the end of the cycle, when they have arrived at about latitude 8°. Two or three years before their final disappearance at low latitude, fresh disturbances are seen to take place in higher latitudes and thus a new cycle is commenced.

At minimum sunspot activity there are, therefore, four distinct belts of disturbances: two near the equator, where the spots are dying out, and two in higher latitudes, where a new cycle is beginning before the preceding one has run its course. Fig. 32 illustrates for the last three cycles (from 1901 to 1931) the course of events described above, as does also Fig. 33.

Maunder represents in the diagram the spots observed for three and a half cycles, from 1874 to 1913, by a number of lines of lengths proportional to the diameter of the spots; the mean ordinate of the lines gives the latitude of the centre of each spot and the abscissa the date of observation. The diagram clearly shows the characteristics of the phenomenon of sunspots, viz. the repetition of the cycle, the limitation of the zones in which they appear and the shift in latitude during the course of the cycle.

Regarding faculae it may be stated that their activity follows the variations of sunspots in so far as the faculae are situated close to or around the spots, but there are also faculae in higher latitudes, namely, between 75° and 80°, according to the researches of Mascari. The generation of these faculae seems to be due to different causes from those which produce faculae occurring at low latitudes or at all events the former do not acquire the same energy as the latter. We shall see

later what relationship exists between sunspots, faculae and prominences.

At the end of 1933 we were at an epoch of minimum sunspot activity; it is interesting to note what have been the characteristics displayed by this last cycle, which began in August 1923, and attained its principal maximum in June 1928. This maximum, as against the previous maximum that took place in August 1917, makes a period of 10·8 years, which

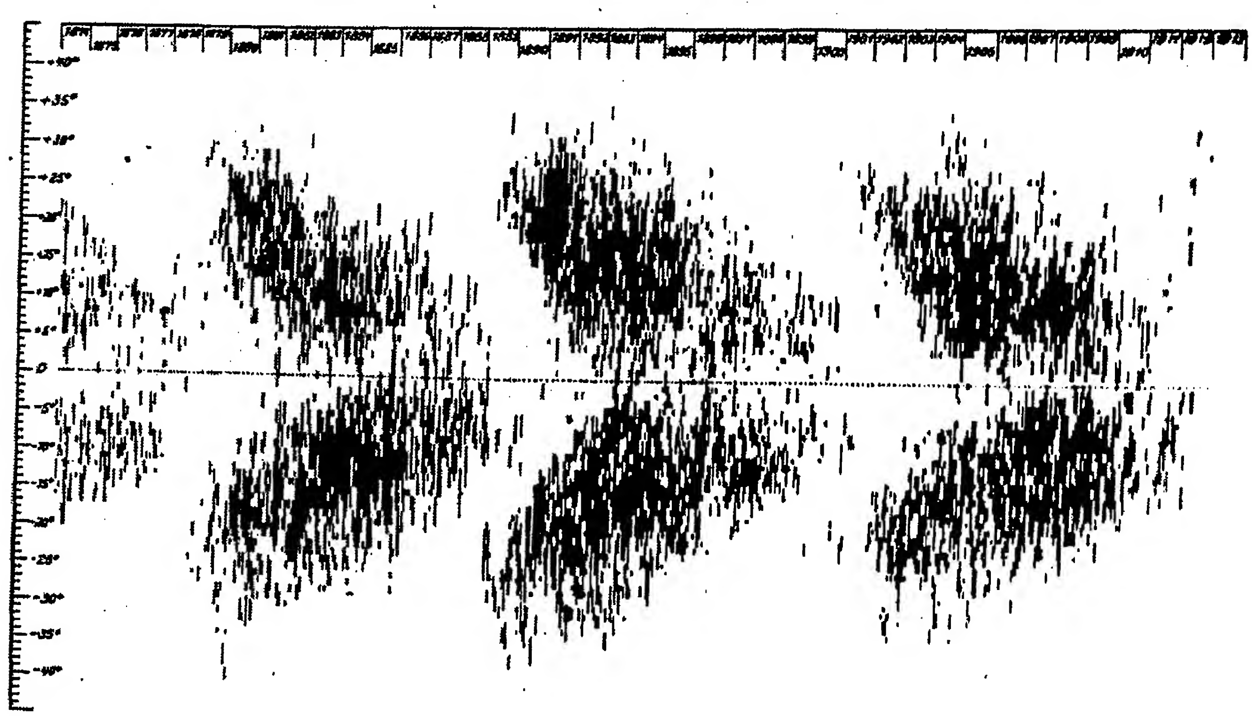

FIG. 33. Distribution of sunspot centres in heliographic latitude from 1874 to 1913 (Maunder).

differs but little from the mean period of 11·1 years. Between a maximum and the last minimum (August 1923) there is thus a time interval of 4·8 years, this interval also being only slightly less than the mean value of 5·2 years. The last maximum may be said to have been of medium intensity with respect to the others, and is equal, as regards trend and intensity, to that of 1829.

Brunner notes that the presence, in the curve of the observed Wolf numbers, of a series of periodic secondary waves which follow each other with great regularity at almost equal intervals of time, seems to be a characteristic of the maxima of medium and low intensities.

Among the maxima of the last hundred years, those of 1829, 1894, 1906 and 1928—which are of medium or low intensity

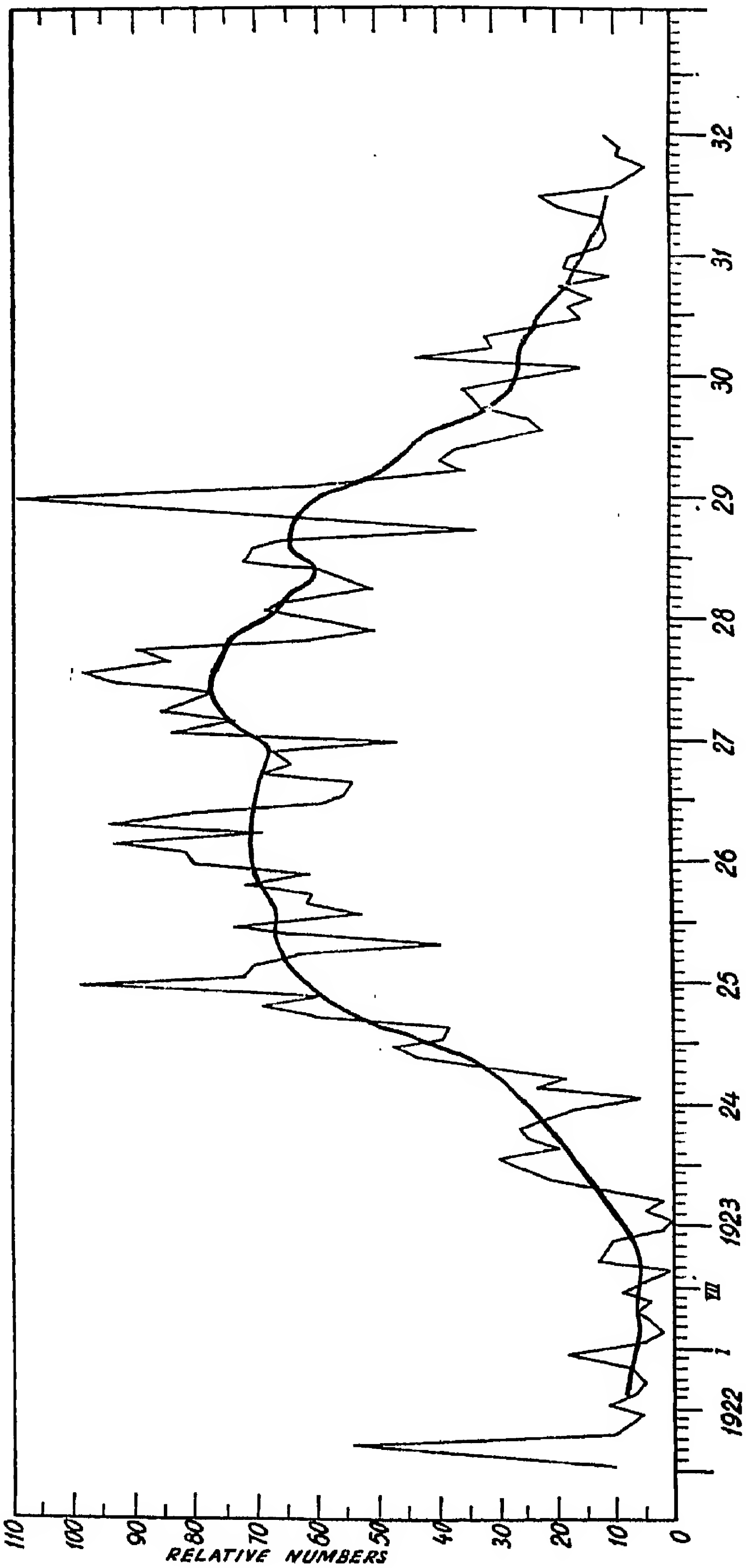

FIG. 34. Relative numbers of sunspots in the last cycle, 1922–1933 (Brunner).

—present a regular sequence of secondary maxima. The maximum of 1829 has four secondary waves with maxima at

equal intervals of 11 months, the maximum of 1894 three secondary waves with intervals of 12 and 11 months, that of 1906 five secondary waves with intervals between 7 and 11 months, and the last maximum of 1928 three secondary waves with intervals of from 15 to 17 months.

Period of Rotation of the Sun, deduced from Sunspots and Faculae; their proper motion; inclination of groups of Sunspots to the solar equator

We have stated that the period of solar rotation, deduced from the movement of sunspots, is 25·35 days, but this is a mean value which refers to spots near the equator; for others at a higher latitude higher values are obtained. Spörer and Carrington, from their long and systematic series of observations, found values which agreed fairly well with one another, but the discrepancies with those of other observers were not accounted for until later, again by Carrington, who demonstrated that the sun's rotation is not that of a solid body, but varies as a function of latitude. The period of rotation is a minimum at the solar equator and gradually increases towards the poles, the values being approximately as follows:

Latitude	*Period of rotation in days*
0°	25·0
10	25·2
20	25·7
30	26·5
40	27·4

The last value is uncertain by reason of the small number of spots occurring at that latitude, observations having been scarce as a consequence. We shall see later how, by the spectroscopic method, the data may be extended to higher latitudes.

Several attempts have been made to represent analytically, with an empirical formula, the velocity of rotation as a function of the heliographic latitude. Many such formulae have been calculated by different observers, and all are more or less of the same form, that is, with a fixed term and a term depending on latitude.

If we indicate the diurnal angular speed of rotation, i.e. the angle traversed by the spots in one day, by ξ, then it is obvious that, if the sun rotated as a solid body, ξ would prove equal to a constant; but, on the contrary, we have for example the following formulae given respectively by Spörer and Maunder:

$$\xi = 8{\cdot}55^\circ + 5{\cdot}80^\circ \cos\phi$$
$$\xi = 12{\cdot}43 + 2{\cdot}01 \cos^2\phi$$

Taking the mean value of the most reliable measurements we obtain the following data:

Latitude	ξ (*spots*)
$\pm 0^\circ$	$14{\cdot}40^\circ$
5	14·38
10	14·31
15	14·20
20	14·06
25	13·89
30	13·69
35	13·47

with a difference of about one degree in the angular velocity of the sun between the equator and the 35th parallel. These values are the result of a very large number of sunspot observations, but as regards their accuracy it should be noted that great differences exist between the results of individual observers because of the proper motion of the spots over the sun's surface.

A determination of the period of rotation has been undertaken at Greenwich Observatory from long-lived spots only, viz. from those which have a life of at least twenty-five days and which are generally regular and fairly circular in shape. In the majority of cases these spots are the leaders of each group. By reason of their regular shape as well as their long duration, they lend themselves very well to the determination of solar rotation. For the last four cycles, from 1878 to 1923, the angular sidereal diurnal motion deduced from 449 spots is found to be:

$$\xi = 14{\cdot}37^\circ - 2{\cdot}60^\circ \sin^2\phi.$$

The proper motion of the spots may be manifested in longitude and in latitude, both irregularly and systematically. For spots of long duration the systematic movements have been

studied at Greenwich, with the result that the movements in latitude have been found to be extremely small, attaining only a tenth of a degree per rotation. Moreover, the general drift of sunspot belts towards the equator in the course of the solar cycle (which should be a mean of 0·14° per sidereal rotation) cannot be traced in the individual movements of the spots.

The systematic motion in longitude, on the other hand, is of much greater importance. As early as 1913 Maunder suggested that this motion is connected with the age of the spots. At the birth of a group we can generally distinguish two principal spots: the "leader" in the direction of the sun's rotation, i.e. towards the west, and the "follower" towards the east. During the first two days of its existence the leader of a group of spots shows a rapid advance in longitude of about 1·0° per day. In the course of the next two days the velocity decreases to 0·4° per day and continues to decrease until about the fifteenth day, after which the spot moves at the mean velocity peculiar to its latitude. About the twentieth day the spot has a slow retrograde motion of about 0·06° per day. Corresponding changes take place in the size of the spots; they increase rapidly at first and attain their maximum about the ninth day, after which they slowly decrease. The area becomes a maximum at about the same time, both for spots with a life of about sixty days and for those of shorter duration.

Fig. 35 depicts the path described by the leader spot: in the upper curve the ordinates represent the shift in longitude, the ascending part of the curve indicating a movement towards the west, i.e. in the direction of the sun's rotation; in the lower curve the ordinates represent the area of the spots in millionths of the visible hemisphere; for both curves the abscissae give the age of the spots in days.

The movement of the follower is always slower than the mean velocity corresponding to its latitude, especially at the time of formation, when the mean velocity is 0·3° towards the east. The simultaneous changes in area show a rapid increase to a maximum towards the third or fourth day, followed by a gradual decrease. From the evidence of spectroscopic observations it must be admitted that the various strata of the solar atmosphere have an angular velocity of rotation which increases with the height above the solar surface. Therefore, if

the differences in the rotational period found for the leader spots are due to their variations of level, it must be concluded that the spots are situated at a higher level at the time of their formation and descend rapidly into the lower strata, in the course of which process their dimensions decrease.

It might be thought, as D'Azambuja observes, that the forces acting at the time of formation of a group tend violently to separate the leader from the follower, and that when the

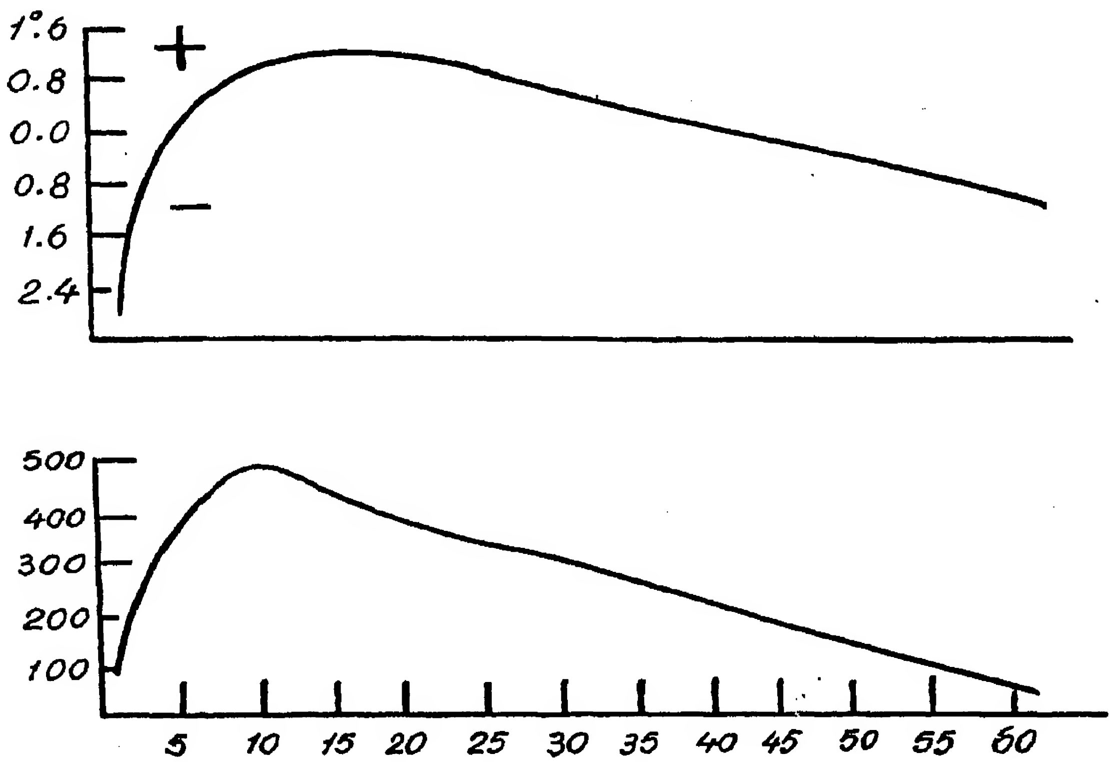

FIG. 35. Mean drift in longitude and variations in area of the leader spots of long-lived groups.

initial impulse has died away the motion of the spots is checked by the viscosity of the medium. The subsequent motion of separation, more especially in the case of the main spot, agrees with the actual velocity of the layer in which the spot is situated; this velocity is therefore slightly less than that derived from the formula deduced above for long-lived spots.

Another characteristic of these sunspot groups, formed by a pair of nuclei more or less far apart which often resolve themselves into several components and which possess well-defined magnetic fields, is that the axis of the group is usually inclined to the solar equator to a greater or lesser degree.

A study made by Joy of the drawings of Carrington and Spörer and subsequently followed up in greater detail by Brunner, who used far more copious observation material, leads to the conclusion that at low latitudes the axis of a group of sunspots is nearly parallel to the solar equator; the mean inclination increases with the heliographic latitude up to 19° and does so in such a direction that in the sense of the sun's rotation the leader is always nearer to the solar equator.

Brunner also shows that there is a relationship between the mean inclination of the axis of the sunspot group and its next stage of development. According to him we may divide

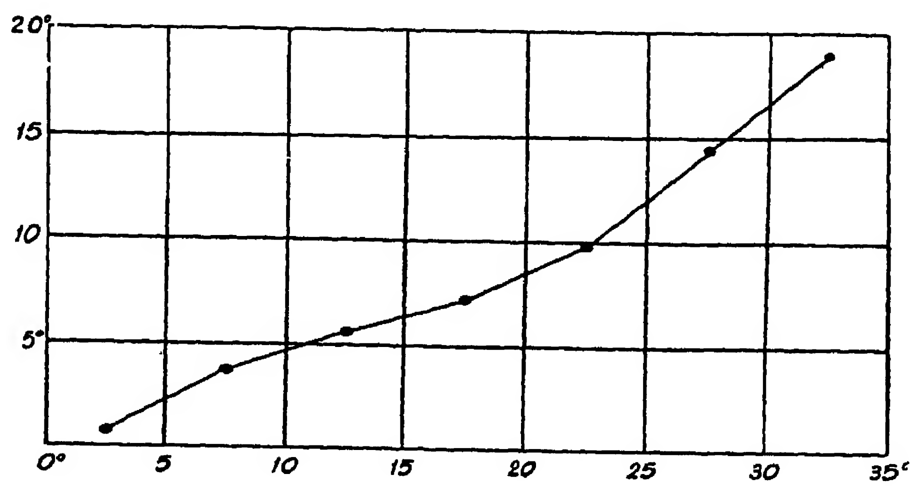

Fig. 36. Variation of the mean inclination of the axis of sunspot groups as a function of the heliographic latitude.
(Abscissae: heliographic latitude; ordinates: mean inclination.)

the groups into three types. The first type comprises those which are at the commencement of their development, the spots being small; the second type those in which the two spots are already formed and divided into leader and follower, often with numerous spots in between, while the third type comprises groups in which these latter spots have disappeared so as to leave only the main spots: the leader and the follower. From about a thousand spots for each of these three types which appeared during the period 1906–1928, Brunner infers that the inclination of the groups on the equator is dependent on the stage of development, in the sense that it decreases with increasing age of the groups, the mean values being:

Group I	7·8°
Group II	6·5°
Group III	4·6°

This course of events is probably connected with the proper motion in longitude referred to in the foregoing. The advance of the main spot in the first stage of development of the group and the decrease of inclination of their axis as their development continues, are aspects that differ from the phenomenon mentioned, both being dependent on the same unknown processes which produce it.

Apparent displacements of sunspots either in latitude or in longitude, due to the presence of the solar atmosphere and depending on the level at which the spots are situated in that atmosphere, have been noted by several observers. Indeed, when a spot is near the limb we observe it obliquely through the solar atmosphere, so that from the earth, owing to an effect of solar refraction similar to that of terrestrial refraction, we shall continue to see the spot after it has passed beyond the limb, and hence we shall deduce an erroneous value for the velocity of the sun's rotation through observing the spots in those particular positions. Hence, if the spots are cavities in the sun's surface, it will be necessary to take into account their depth if we wish to find a period of rotation related to the level of the photosphere.

The determination of the period of solar rotation from observations of faculae is difficult and inaccurate, because faculae do not constitute well-defined points of reference as is ordinarily the case with sunspots; moreover, they are only seen near the solar limb. On the other hand, they offer an advantage over sunspots in that the groups of faculae are generally longer-lived. The more extensive determinations are those effected by Maunder from photographs taken at Greenwich during the period from 1888 to 1893. Small isolated areas visible in faculae have been identified by Maunder at intervals of a complete rotation, with the following results:

Northern and southern belts	*Mean sidereal rotation in days*	ξ
°	°	°
0 to 10	24·88	14·47
10 to 20	25·08	14·35
20 to 30	25·60	14·06
30 to 40	25·59	13·54
45	28·06	12·83

From these results he obtains the following empirical formula:

$$\xi = 14 \cdot 54^\circ - 2 \cdot 81^\circ \sin^2 \phi$$

The various rotational periods derived from the different solar phenomena will be compared later, after we have dealt with the results obtained by the spectroheliographic and spectroscopic methods.

The proper motion of faculae has also been investigated at Greenwich Observatory by comparing their mean latitude during one rotation with the mean latitude during the succeeding rotations. The results would suggest that faculae have a proper motion away from the equator of $0 \cdot 8^\circ$ per sidereal rotation between 0° and 40° latitude; in higher latitudes this motion seems to be more pronounced.

Shape of the Sun and its Probable Variations

Systematic measurements of the sun's diameter in different latitudes were commenced as early as 1750 by Bradley and, besides the problem of a possible secular contraction of the sun's diameter, the question of the sphericity of the solar globe and the variability of its diameter during the various phases of solar activity have also been discussed. The measurement of the diameter was and is still carried out with meridian circles, the horizontal diameter being determined by taking the times of transit of the west and east limb, whilst the vertical diameter is measured by the difference in declination between the north and south limbs. Heliometers and photography are also used for this purpose.

Father Secchi and Father Rosa of the Collegio Romano studied the variations of the solar diameter by using the observations then available; the latter, in a detailed memoir, concluded that at epochs when the number of sunspots and prominences is a minimum, the equatorial diameter is at its greatest. Discussing the observations made by Hilfiker with the meridian circle, R. Wolf obtained a result for the sunspot of 1870 (the largest maximum known) in agreement with what he calls the "Secchi–Rosa law."

Systematic observations of the transit of the solar diameter which demonstrate its variability have also been carried out

at the Campidoglio Observatory ever since 1877. But it is difficult to establish in how far this variability is characteristic of the sun or due to other causes.

Meanwhile the problem is probably complicated by the fact that the two diameters, polar and equatorial, show a slight difference which varies with the cycles of activity. According to Lane Poor, who examined observations made by several investigators with different methods, the relationship between the polar and the equatorial diameters varies periodically. The length of the period is uncertain, but seems to be approximately that of the sunspot cycle. The amplitude of these variations is about 0·2″, the difference between the maximum positive and negative values being about 0·5″.

At Greenwich the sun's diameter is observed regularly with the meridian circle, and from a discussion of observations made during the decennial period 1915–1925 it appears that the vertical diameter exceeds the horizontal by 0·3″, which difference may be partially due to the different method of observation, the horizontal diameter having been measured at transit with a recording micrometer, whilst the vertical was found by measuring with meridian circles the difference in zenith distance between the north and south limbs

The results of examining the relationship between the diameters observed and the sunspot period are inconclusive; on the other hand if, for every month during the decennial period, the differences between the diameters calculated in the *Nautical Almanac* and the diameters observed are tabulated for the two diameters, we find maximum variations amounting to one second of arc; the diameters observed are larger in summer than in winter.

Discussing the various causes which may produce these differences, we arrive at the conclusion that they may be due to irradiation and to its variation in the course of the year. Indeed, the hypothesis has been propounded that irradiation varies with atmospheric absorption at different altitudes of the sun above the horizon, and also with the varying contrast between the luminous disc of the sun and the background of the sky. Cullen, discussing the Greenwich observations, finds that the variations in diameter are proportional to the secant of the zenith distance of the sun, attaining exactly one second

of arc. On the other hand the total effect of irradiation on the sun's diameter, which has a mean value of 1920″, seems to be 3″. From this it is concluded that the annual variations of the sun's diameter due to irradiation are considerable, and hence it is not surprising that some difficulty is experienced in distinguishing from this apparent variation a possible real variation of the solar globe.

The problem is far from being solved; it would seem necessary to devise more precise methods of measurement and to make the observations in places where the variations due to terrestrial causes are as small as possible. That there may be a difference between the polar and the equatorial diameter of the sun and that this difference may be variable, is possibly confirmed by the fact that there seem to be variations in the sun's outer envelope (called the "chromosphere"), and by the fact that very considerable variations occur periodically in the more external envelope, viz. the solar corona which is visible to us only during total eclipses.

It has already been noted by Respighi that the height of the chromosphere varies at different latitudes; from the regular observations effected at Arcetri during the last cycle it would appear that during the epochs of minimum solar activity the chromosphere is higher at the poles than at the equator, whereas during the epochs of maximum activity the height of the chromosphere is approximately the same around the whole border (page 133).

As we shall see, the solar corona shows well-defined configurations with varying distribution of coronal matter, now at the equator, then at the poles, according to the maxima and minima of solar activity.

CHAPTER III

WHAT IS SEEN ON THE SUN BY SPECTROSCOPIC OBSERVATION

Spectrum of the Photosphere

If we project the sun's disc on the slit of an ordinary spectroscope, we obtain a continuous spectrum furrowed with numerous absorption lines discovered by Wollaston in 1802, and independently by Fraunhofer in 1814. Fraunhofer made a detailed examination of them, indicating the principal ones by letters of the alphabet in progressive order from red to violet and so designing the first map of the solar spectrum. These absorption lines, which took their name from him, acquired great importance later on when, thanks to the discovery of Kirchhoff and Bunsen, it became possible to understand in what manner and from what elements they have been produced.

The solar spectrum generated by the luminous disc of the sun belongs to the photosphere and is, on the whole, always the same as regards number, position, and intensity of the lines when we examine a region at or near the centre of the disc not disturbed by spots or eruptions. The spectrum with its colour-sequence can be perceived visually from violet (about 4000 A) to dark red (about 7000 A), but without it being possible to indicate exact limits, as this depends on the individual sensitivity of the eye to the various colours and on the brightness of the spectrum. With photography these limits, towards either the violet or the red, are considerably extended, and still more so if special means of observation are employed such as quartz spectrographs for the ultra-violet regions and spectrographs with rock-salt prisms for the infra-red regions of the spectrum.

After Fraunhofer's time, charts of the solar spectrum were drawn with increasing accuracy until it became possible to use photography. The most complete and accurate chart is that made by Rowland, actually by photography, with a

concave grating of great dispersion. The total length of the spectrum on Rowland's chart is 13 m and contains 20,000 lines, from 2975 A to 7331 A. This chart has on it a graduated scale enabling the various wavelengths to be estimated to within a hundredth of an angstrom, each division being equal to 3·3 mm. Moreover, the chart is accompanied by a table which Rowland himself calls the "Preliminary table of solar spectrum wavelengths," reproduced in the first volumes of the *Astrophysical Journal* (1895–1897), which gives for each wavelength, to within a thousandth of an angstrom, the intensities estimated by the eye on an empirical scale and, where possible, their identification with known terrestrial elements. In this scale the most intense lines of the solar spectrum, which are the two calcium lines (indicated by the letters H and K), in the violet region of the spectrum, have respectively the intensity 1000 and 700, while the faintest lines visible in Rowland's photographs are indicated by 0000.

The wavelengths given by Rowland are based on a fundamental datum, viz. the wavelength D_1 of sodium, and on relative comparisons in the spectra of the various orders. Since, according to more recent measurements, the wavelength of the line in question differs from that used by Rowland by about 0·2 A, and since, moreover, it has been found that the wavelengths of the solar lines are, for various regions, not the same as they would be if the lines were produced in vacuo, the necessity arose of adopting an international wavelength system based entirely on terrestrial light-sources. The primary standard selected was the wavelength of the red line of cadmium, which could be measured directly in terms of the standard metre, with an error of less than one thousandth of an angstrom; the secondary and tertiary standard lines are those of the iron arc, whose wavelengths were brought into relationship with that of the red line of cadmium by interferometric methods of great accuracy.

With the aid of those fundamental lines and with powerful instruments such as the 50-metre tower and the 23-metre spectrograph, Rowland's measurements were carried out afresh at Mount Wilson, and in 1928 St. John and his collaborators published a *Revision of Rowland's Preliminary Table*. This table sets forth the wavelengths of the Fraunhofer lines from 2975 A

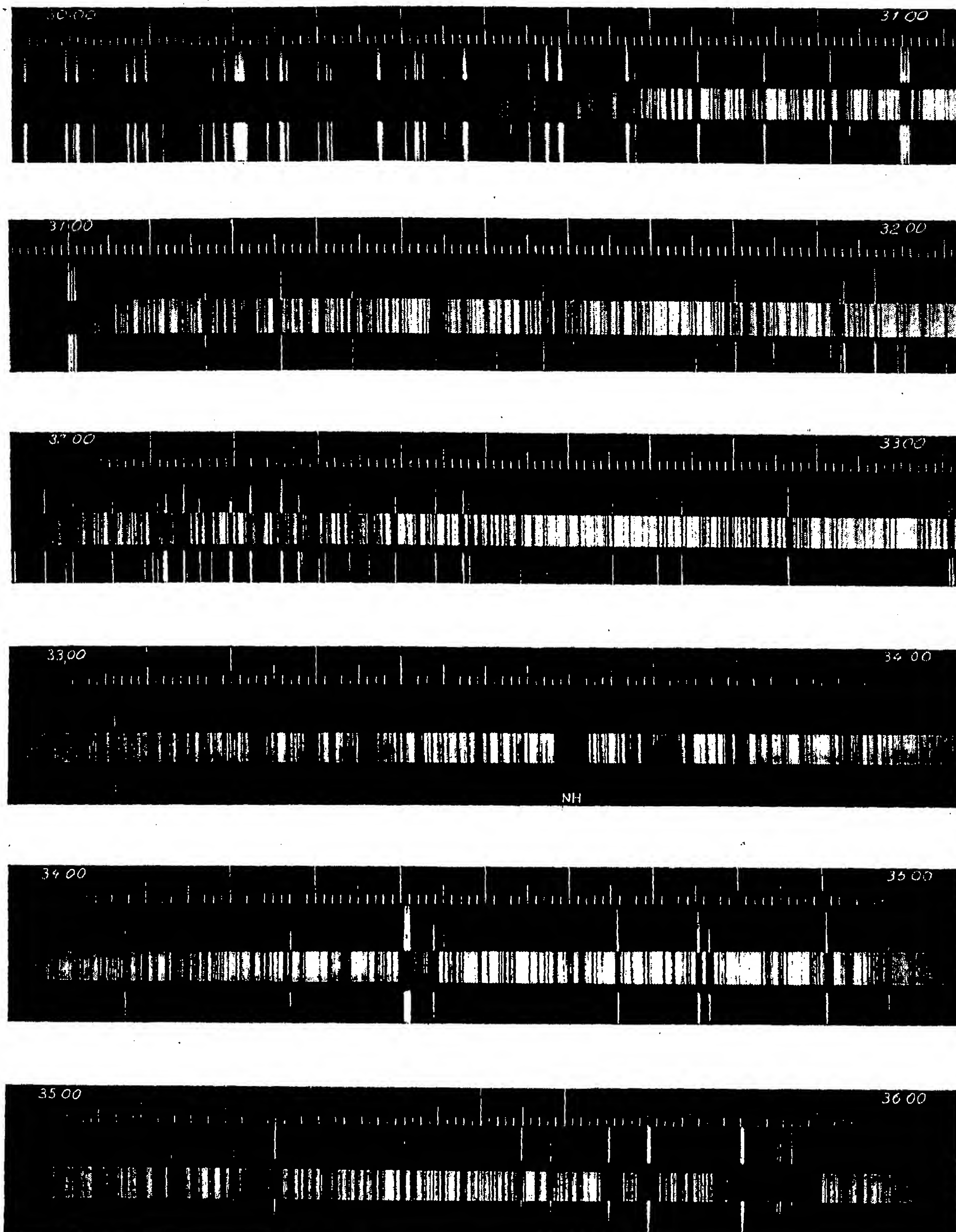

FIG. 37. Solar spectrum with comparison spectrum of the iron arc from 3000 A to 3600 A.

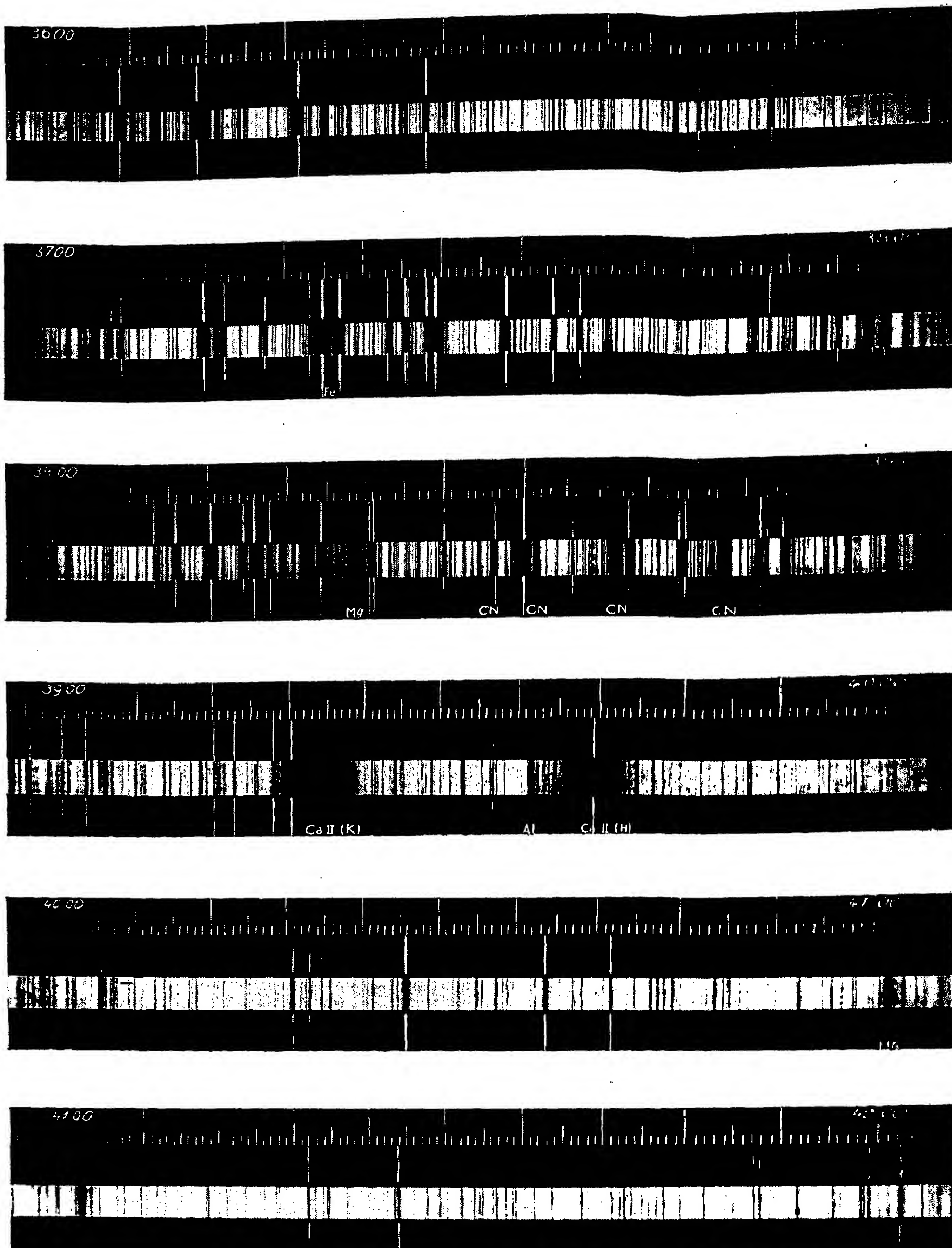

FIG. 38. Solar spectrum with comparison spectrum of the iron arc from 3600 A to 4200 A.

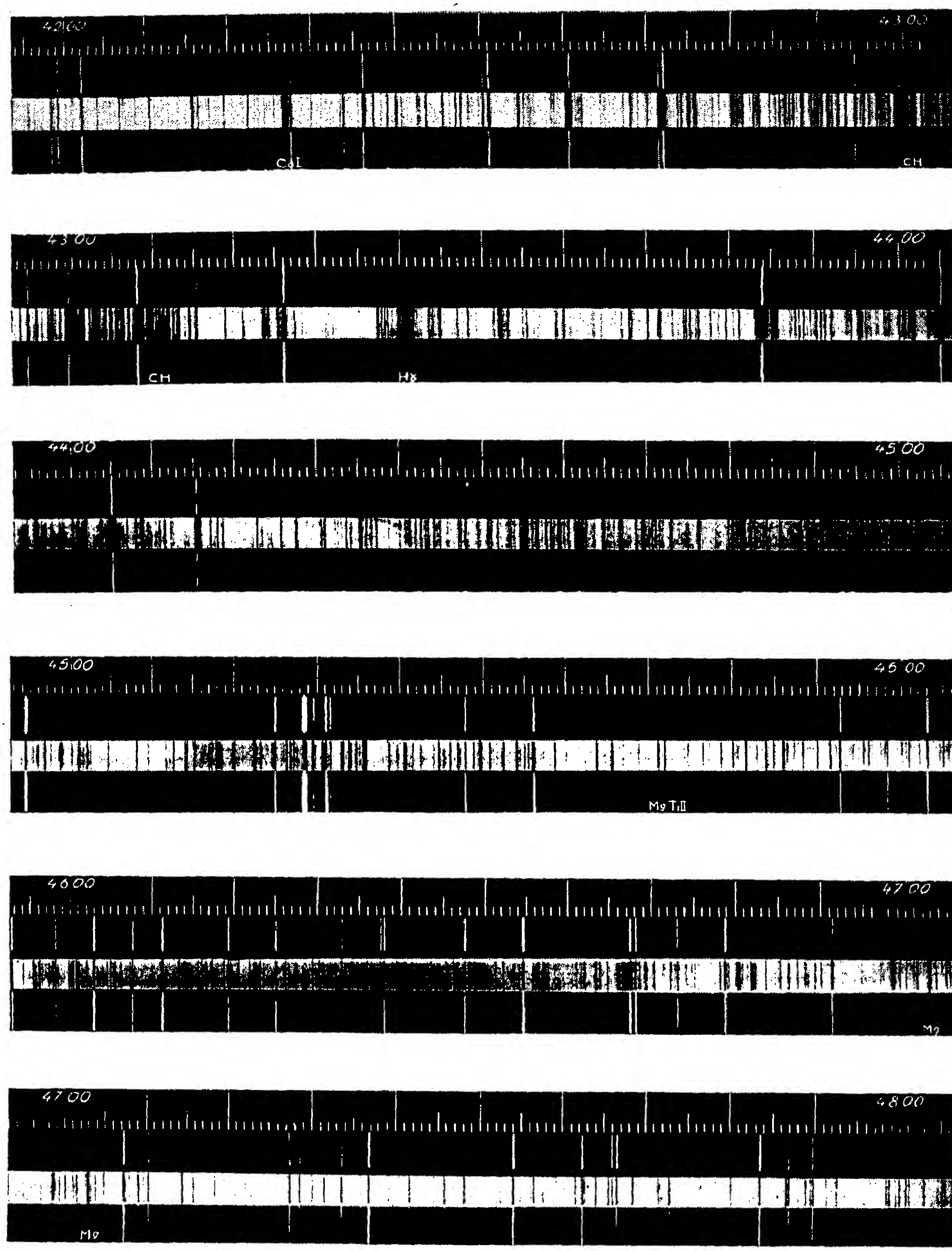

Fig. 39. Solar spectrum with comparison spectrum of the iron arc from 4200 A to 4800 A.

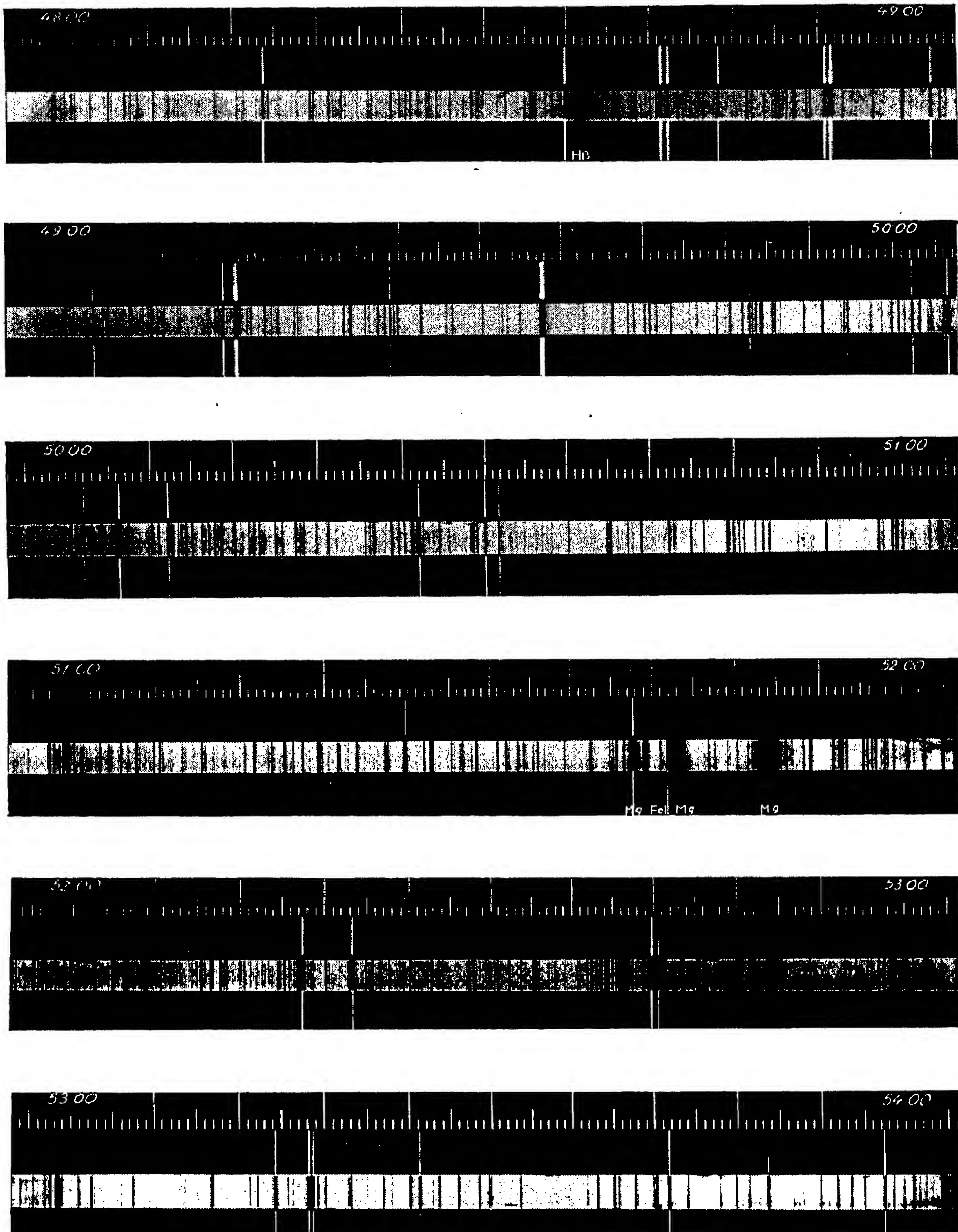

Fig. 40. Solar spectrum with comparison spectrum of the iron arc from 4800 A to 5400 A.

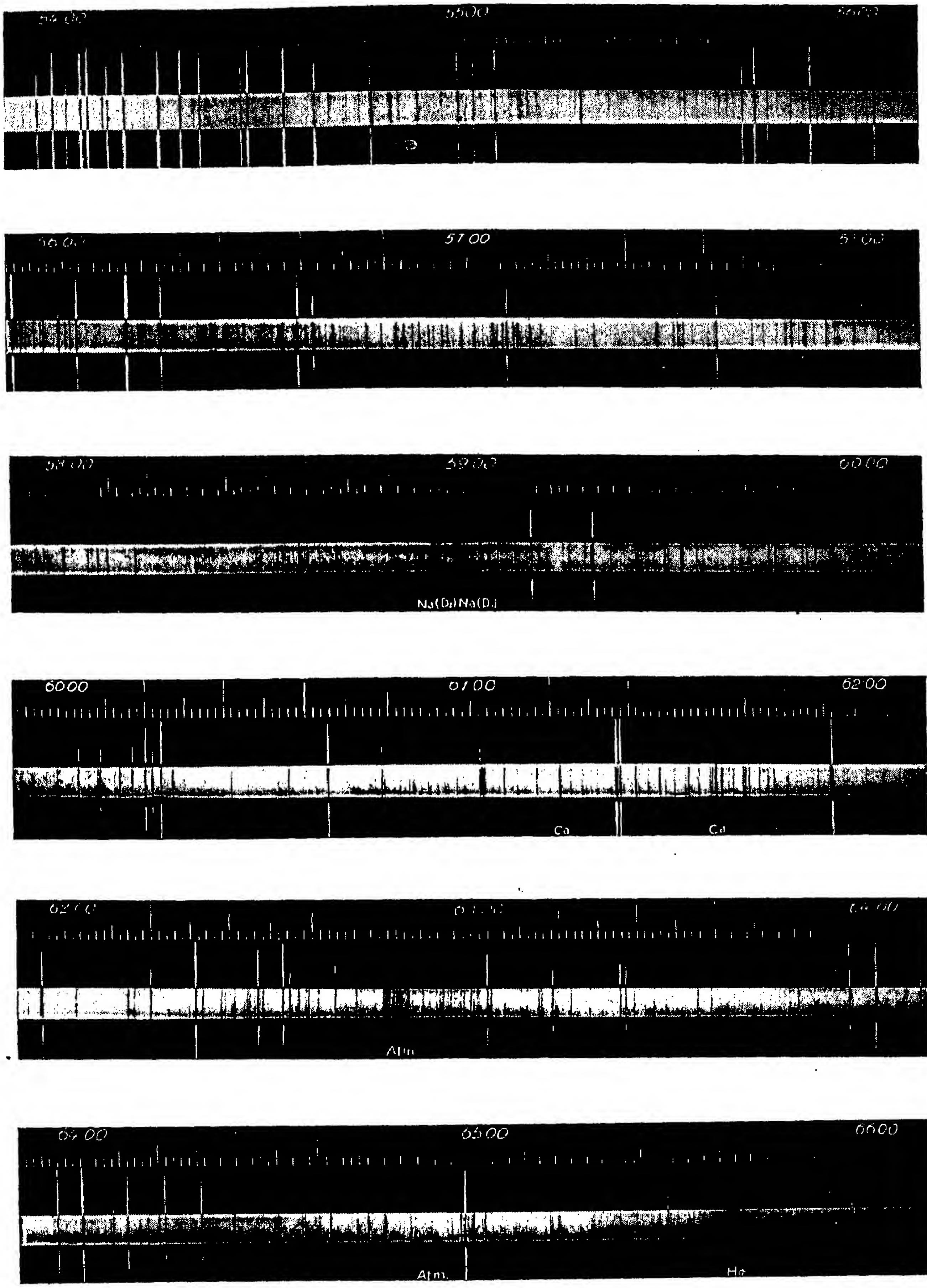

Fig. 41. Solar spectrum with comparison spectrum of the iron arc from 5400 A to 6600 A.

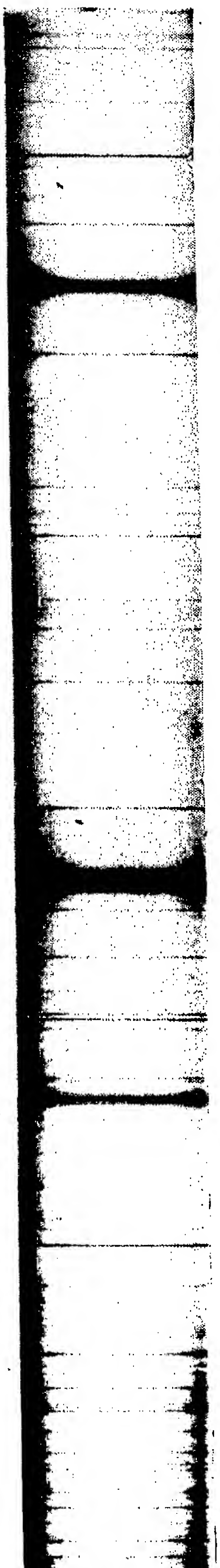

FIG. 42. The strong infra-red lines of ionized calcium at 8498 A–8548 A–8662 A (Babcock).

to 7331 A in the new international system and adds some 2,000 lines in the infra-red region from 7331 A to 10219 A, giving many new identifications and showing the intensity of lines not only on the solar disc but also on sunspots. The faint lines, instead of being marked from 00 to 0000 as in Rowland's table, are indicated in the *Revision* by the negative numbers from 0 to — 4.

The advancement of spectroscopy in recent years has been so far-reaching that we have not only gained more knowledge concerning spectra obtainable in the laboratory from the elements found on the earth, but we are also beginning to understand something of the mechanism whereby spectra are produced. Hence not only have more numerous identifications been established between the lines produced in the laboratory and the Fraunhofer lines, but it is also known to what state of energy of the elements the lines correspond.

In addition to many new identifications the *Revision* gives, for a large number of lines, the temperature and pressure classes to which they belong. The electrons surrounding the nucleus vibrate under various circumstances with greater or lesser energy, giving rise to the different spectral lines. When the excitation of the atom increases, one or more electrons may escape the action of the nucleus and then, instead of a neutral atom, there is an atom ionized one or more times, with the consequent production of a new set of lines which is easily recognizable and which, as far as is feasible with our laboratory resources, can be reproduced on the earth by increasing the degree of excitation, as for instance from a simple flame to the electric arc or spark.

The work required for ionizing the atom is defined as the ionization potential, which

corresponds to that atom and is ordinarily expressed in volts.

The neutral atom in the *Revision* is indicated by the simple symbol corresponding to the element, as for instance *Ca* for calcium, the singly-ionized atom by Ca^{+}, the doubly-ionized atom by Ca^{++}, etc. According to more recent conventions the atoms ionized once or twice respectively are indicated as *Ca*II and *Ca*III, the indication *Ca* or *Ca*I being reserved for the neutral atom.

As already stated, most of the Fraunhofer lines are due to neutral atoms of those elements which possess a high ionization potential, and to ionized atoms of those having a low ionization potential. While reserving for later discussion the hypotheses that may be put forward regarding the quantity of the various elements composing the sun, we may state that the identifications which have been more or less established up to the present can be catalogued as follows:

ELEMENTS CERTAINLY PRESENT IN THE SUN

Hydrogen	Calcium	Yttrium	Neodymium
Helium	Scandium	Zirconium	Samarium
Lithium	Titanium	Columbium	Europium
Beryllium	Vanadium	Molybdenum	Gadolinium
Barium	Chromium	Ruthenium	Dysprosium
Carbon	Manganese	Rhodium	Erbium
Nitrogen	Iron	Palladium	Ytterbium
Oxygen	Cobalt	Silver	Lutetium
Sodium	Nickel	Cadmium	Hafnium
Magnesium	Copper	Indium	Tungsten
Aluminium	Zinc	Antimony	Osmium
Silicon	Gallium	Barium	Iridium
Phosphorus	Germanium	Lanthanum	Platinum
Sulphur	Rubidium	Cerium	Lead
Potassium	Strontium	Praseodymium	

ELEMENTS PROBABLY PRESENT IN THE SUN

Tin	Terbium	Thallium

ELEMENTS NOT OBSERVED IN THE SUN

Fluorine	Krypton	Tantalum	Radon
Neon	Masurium	Rhenium	Radium
Chlorine	Tellurium	Gold	Actinium
Argon	Iodine	Mercury	Thorium
Arsenic	Xenon	Bismuth	Protoactinium
Selenium	Caesium	Polonium	Uranium
Bromine	Holmium		

Of the 22,000 lines figuring in the *Revision*, only 12,000 have been identified, i.e. 57 per cent. Although there is still much work to be done in order to become fully acquainted with the origin of the solar spectrum, it must nevertheless be acknowledged that the most intense Fraunhofer lines have all been identified. It is evident that even if all the lines could be identified they would not establish the presence of all the ninety-two chemical elements known on the earth, either because the strongest lines of the element occur in an unfavourable region of the spectrum or because of the small quantities in which certain elements seem to occur on the sun.

Besides the separate lines, various regions of the spectrum of the solar photosphere show lines in dense groupings which, on account of their characteristic appearance, are referred to in spectroscopy as *bands*, and are due to vibrations of molecules. Their presence tells us that the elements in the photosphere must be in such states of temperature and pressure as to permit of their continued existence without decomposition into their constituent atoms.

According to the identifications hitherto accepted the principal bands are due to cyanogen (*CN*), to the carbon molecule (C_2, *Swan bands*), to the hydrides *CH*, *NH*, *OH*, to the hydrides of aluminium, magnesium, calcium, and to the oxides of aluminium, titanium, zirconium; some of them, as we shall see, are much more intense and occur only in the spectrum of sunspots.

On Rowland's map, after the two very intense lines visible in the violet which are due to ionized calcium, the line $H\alpha$ of hydrogen is conspicuous in the red: it is the first of the *Balmer series*, whose other lines $H\beta$, $H\gamma$, $H\delta$ are also clearly visible in the violet. Noteworthy, too, are the sodium lines in the yellow and those of magnesium in the green. Below the wavelength 2900 A all solar radiations are absorbed by the terrestrial atmosphere, and for this reason we know nothing of the far ultra-violet region of the solar spectrum; towards the red, beyond the line $H\alpha$, are characteristic bands with well-defined lines which Fraunhofer denoted by the letters A, B, which are now recognized to be due to the oxygen of our atmosphere. The latter acts as a filter and absorbs these particular radiations more or less thoroughly according to the depth of the

oxygen layer traversed, and hence these bands are very pronounced when the sun is low on the horizon. As many as 6500 of the 22,000 lines now catalogued belong to our atmosphere; they are known as *telluric lines* and have been identified not only with the bands due to the oxygen molecule, but also with bands due to water vapour, ozone and possibly carbon dioxide.

Not all the elements stated in the table appear in the spectrum of the photosphere, and we cannot say that this spectrum is the same at all points on the solar disc; indeed, when we examine a region of the sun disturbed by spots or faculae, or when we observe one in the neighbourhood of the limb or immediately outside it, we find considerable differences from the normal in the Fraunhofer lines and in the distribution of energy in the continuous spectrum.

Spectra of the Solar Limb, Spots, Reversing Layer and Chromosphere. Intensity and Profile of Fraunhofer's Lines

If, with the slit of the spectroscope, we pass gradually from the centre of the solar disc towards the limb, a gradual variation in the spectrum will be noted which is manifested by three different characteristics when we arrive in closest proximity to the limb:

(1) Some of the most intense lines at the centre of the disc, as, for instance, the lines H and K of calcium, do not show clean edges in the continuous spectrum, but a gradual diminution in intensity forming what is termed the *wings* of the line. These wings become fainter and fainter towards the limb, until in some cases they even completely disappear.

(2) Many of the lines widen at the limb, diminishing at the same time their contrast from the continuous spectrum.

(3) Some of the lines become more intense at the limb, others less so, according to the origin of the lines, viz. the energy level at which they are produced. This phenomenon is analogous to that occurring in sunspots.

The differences in the relative intensities of the lines between limb and centre are more marked in the blue, violet, and

ultra-violet regions of the spectrum, and are less marked in the green, yellow, and red regions, except in the case of lines having well developed wings at the centre of the disc, such as those of sodium D_1, D_2, and those of magnesium b_1, b_2, b_4 (Fig. 43). In the region 3815–3840 A the appearance of the spectrum is greatly changed, because the wings which characterize the most intense lines in the spectrum of the centre of

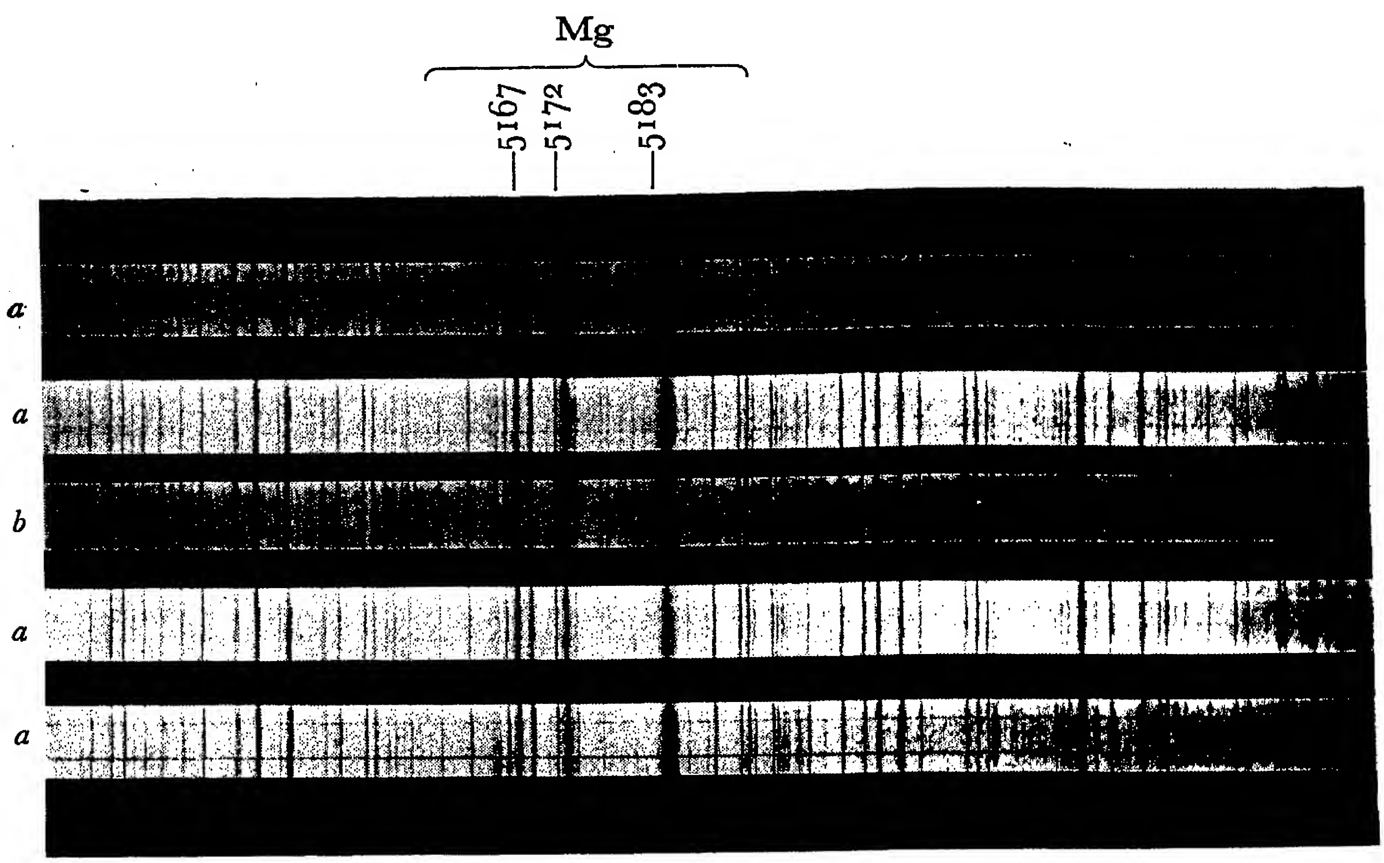

FIG. 43. Spectrograms of the limbs and of the centre of the sun between 5100 A and 5200 A (Arcetri).
(*a:* limbs; *b:* centre.)

the disc have disappeared almost entirely. These effects are probably due to the different depths of the layers which the rays have to penetrate at the centre and at the limb in order to pass out of the solar atmosphere. The absorption of the highest and therefore coolest vapours would naturally produce a change in the relative intensities of the lines similar to that which takes place in sunspots, but to a smaller extent. However, there is no reason to believe that there is any great affinity between the two classes of phenomena.

The features presented by the spectrum of a sunspot are

such as to distinguish it clearly from the spectrum of the photosphere at the centre of the disc, the characteristics of sunspot spectra being such as to enable us to establish the differences in temperature and pressure between the spots and the photosphere. The most outstanding of these characteristics are as follows: The hydrogen lines are fainter than in the spectrum of the photosphere, and the line of neutral calcium, 4227 A, is considerably more intense. In sunspot spectra we see a continuous hydrocarbon band from 4299 A to 4315 A, and the continuous spectrum in the violet diminishes in intensity more rapidly than in the spectrum of the photosphere.

A very large number of lines change their relative intensity; some of them become darker, others less dark, according to the elements to which they belong, or it may happen that for one and the same element some of the lines are more intense and others less so, as compared with the photosphere. Sunspot spectra show a very large number of new lines, many of them grouped together in bands or flutings. A very large number of lines widen and in some cases are doubled or trebled. The characteristics mentioned above may be accounted for by comparing sunspot spectra with spectra obtainable in the laboratory and by examining the distribution of energy in the continuous spectrum.

The strengthening of some lines and the weakening of others indicates a diminution of temperature on the spots as compared with the photosphere, this being confirmed by the appearance of the bands which, in so far as it has been possible to identify them, are due chiefly to titanium oxide and to magnesium and calcium hydrides. It is known through Hale's discovery that the widening and doubling of the lines are due to the Zeeman effect, viz. to the presence of intense magnetic fields in sunspots (page 192).

A photographic chart extending from 4600 A to 7200 A has been prepared at the Mount Wilson Observatory to facilitate the study of sunspot spectra, and a further chart has been made for the study of magnetic fields in particular. These charts plainly show that for some elements, for instance calcium, sodium, chromium, titanium and vanadium, the majority of the lines are more intense in sunspots than in the photosphere; for others, such as hydrogen and silicon, most of the lines are

less intense, whilst for others again, such as iron, cobalt and nickel, some of the lines become more intense and some of them less so.

It can be proved by laboratory researches that all the lines which diminish in intensity in sunspots are those belonging to the category of the *enhanced lines*, viz. those produced by atoms situated at relatively high energy levels or completely ionized levels. The lines that become more intense in the spots are, on the other hand, those due to low excitation of the atom. The theory of ionization will throw more light on these phenomena.

In the region comprised in the Mount Wilson map nearly 5000 lines have been identified as belonging to the bands of titanium oxide, and it was found that their intensity increases towards the larger wavelengths exactly as it increases in the spectrum of the titanium flame. About 600 lines of calcium hydride have been identified in sunspot spectra, and about 500 of magnesium hydride. It may be stated that about 80 per cent of the total number of lines not yet identified individually in sunspot spectra might be attributed to these three compounds.

Since, as we shall see, the solar atmosphere consists for about 90 per cent of hydrogen, the dissociation of all the hydrides must be impeded by mass action, or counteracted by the great excess of hydrogen present. The presence of CaH in particular is indeed significant since it furnishes good confirmation of the applicability of the law of mass action under such conditions, because the energy of formation of the molecule CaH is very small compared with that of the other molecules existing in sunspots (23,000 calories).

With regard to oxygenated compounds, the reduction of oxides as a result of the excess of hydrogen appears to be very marked in the case of elements capable of yielding oxides and hydrides, owing to a peculiar play of equilibrium between oxides, hydrides and hydroxides; the phenomenon is far less pronounced for elements not capable of forming hydrides. The presence of titanium oxide and the absence of magnesium oxide in sunspots may thus be accounted for, although the energy of formation of the former is somewhat less than that of the latter.

Now, on proceeding to examine the spectrum of the highest

layers of the sun's atmosphere, we can distinguish the spectra of the reversing layer, chromosphere, prominences and corona. We will deal here with the first two and then with the others.

Upon directing the slit of a spectroscope of sufficient dispersion at a tangent to the solar disc and observing one of the most intense lines of the spectrum, as for instance the line *Hα*, we find that the wings accompanying the dark line in the spectrum of the photosphere disappear, being transformed into two lines, or rather two luminous components

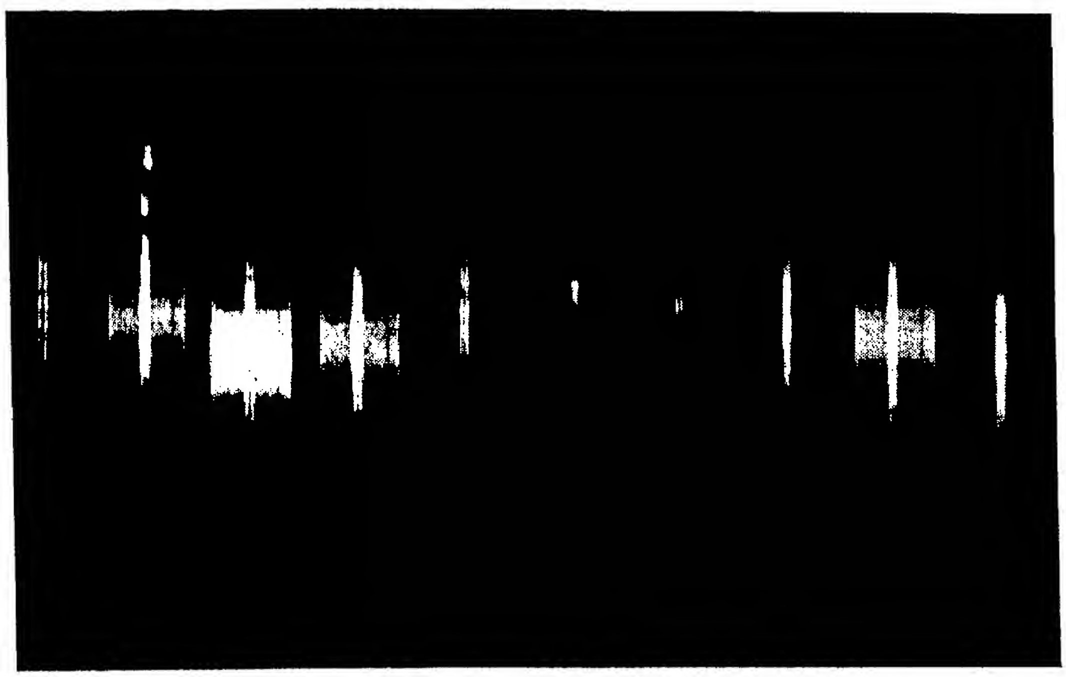

FIG. 44. Reversal of the line *Hα* at the solar limb and on prominences (Arcetri).

of the same line, being more intense than the continuous spectrum, which at the limb is naturally very much reduced in intensity (Figs. 45 and 46). For such positions of the slit we still see the dark hydrogen line, which has, however, become less intense and is accompanied on each side by an emission component. Turning away from the tangent position still further from the disc, the continuous spectrum disappears, and so do the dark lines, while the two luminous components merge into one (see centre of Fig. 44). This phenomenon is common to all the lines, but owing to diffused light from the main part of the sun and to atmospheric disturbances, only the more intense lines can be observed in this way.

In the position of the slit in which luminous com-

ponents begin to appear (viz. the phenomenon which, analogous to what is observed in laboratory spectra, is called "double inversion" of the line) we see what may be considered to be the commencement of the spectrum of the reversing layer or rather of the low chromosphere. This is much more easily observed during a total eclipse of the sun, immediately before the second contact or after the third, viz. a few moments before the moon entirely covers the sun's disc, or a few moments after the moon leaves uncovered all the light emitted by the photosphere. As the solar disc is then covered by an opaque body outside our atmosphere (the moon), all that is left to emit light is the outermost part of the sun's atmosphere, the lowest layers of which consist of all elements that are visible by absorption in the photosphere. Under these peculiar conditions of observation the usual light of the sun's atmosphere is absent, but the atoms of the elements emit, according to Kirchhoff's law, just those radiations which they are capable of absorbing, and hence we see the emission lines in whose central part the absorption component is superimposed, giving rise to the phenomenon of double inversion.

As is well known, the same phenomenon is observed in the laboratory, e.g. in an electric arc, where the intensity and distribution of the vapour which it emits or absorbs are under conditions analogous to those on the sun. Modern theories, to which we shall refer later, explain this process more clearly; meanwhile it may be stated that the spectrum of the reversing layer, called the "flash spectrum" because of the rapidity with which it appears and disappears when the slit of the spectroscope is placed tangentially to the solar disc, or during eclipses, is in some respects the reproduction of the reversed spectrum of the photosphere. Each line in absorption corresponds to a line in emission in the spectrum of the reversing layer, but since the reversing process is complicated because of the height, temperature and density at which that particular element is brought into the solar atmosphere, the relative intensities of the lines vary in different spectra.

If we move the slit of the spectroscope still farther away from the solar limb, the greater part of the lines of weakest emission gradually begin to disappear and only a few of the most intense ones remain. We then observe the spectrum of

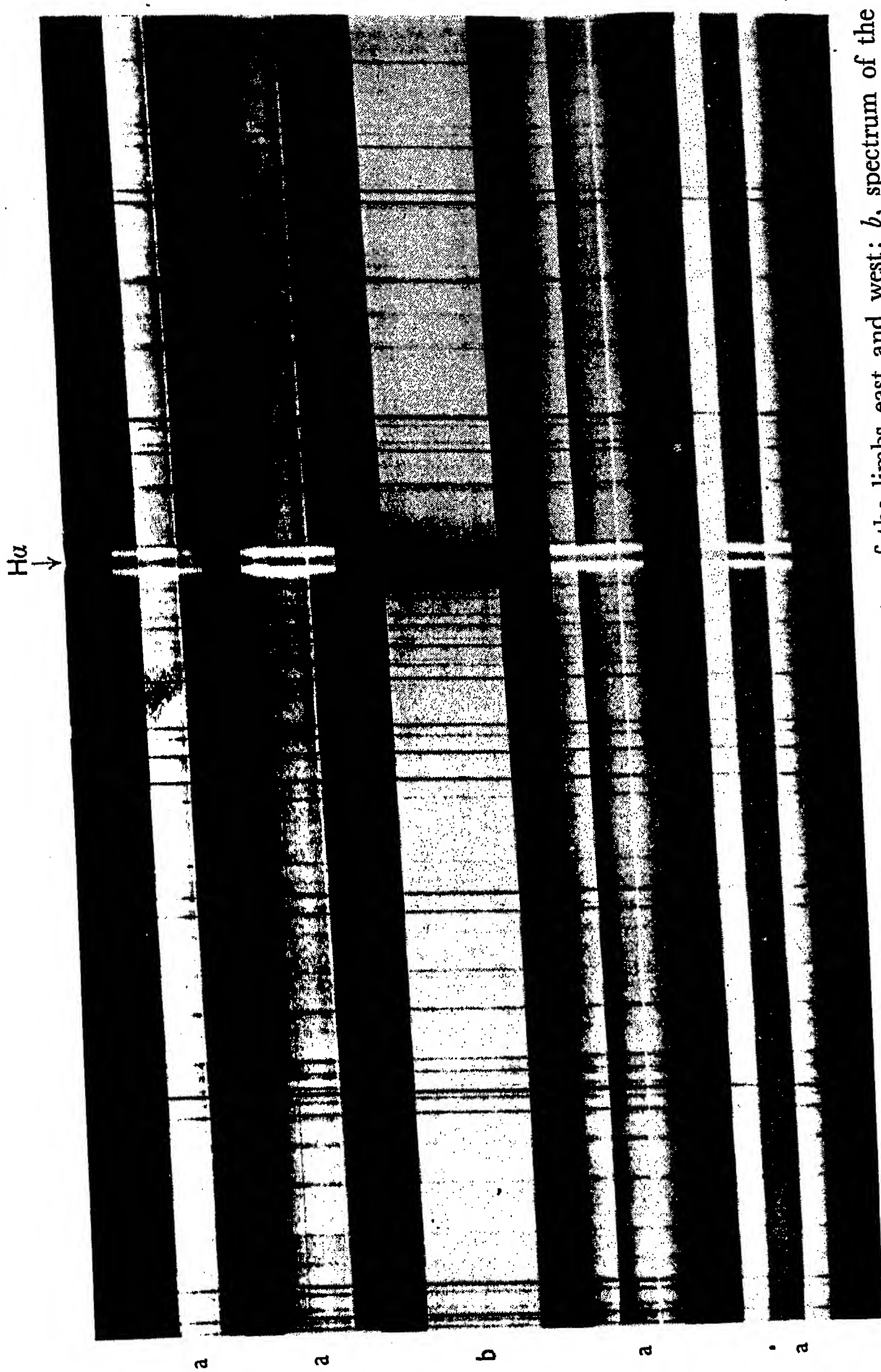

FIG. 45. Inversion of the line $H\alpha$ at the solar limb—*a*, spectra of the limbs east and west; *b*, spectrum of the centre of the sun's disc (Arcetri.)

the highest part of the solar atmosphere, which is termed the chromosphere.

The upper limit of the reversing layer and of the lower layer of the chromosphere may be considered to be located in the zone in which the majority of the Fraunhofer lines end, which zone is calculated to attain a mean level of about 600 km above the photosphere. Above this limit, in the high chromosphere, there only remain such gases as are more abundant in the solar atmosphere, and these attain a mean height of from ten to fifteen thousand kilometres or more as occurs in the phenomenon of prominences, which may also

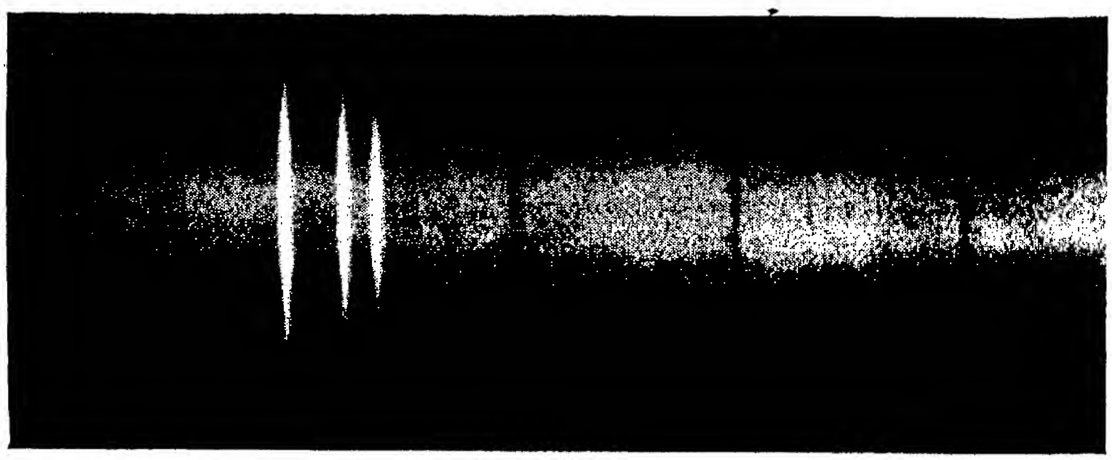

FIG. 46.—Lines of atomic oxygen at 7772–7774–7775 A, inverted at the solar limb (H. W. Babcock).

be considered part of the chromosphere. Of course it should not be thought that a sharp demarcation exists between the two layers, viz. the reversing layer and the chromosphere, for there is a gradual and continuous transition from one to the other, and the nomenclature has originated from the phenomena observed.

In the chromosphere the hydrogen lines of the Balmer series are very pronounced, the brightest of them all being the $H\alpha$ line, which is the one that gives the chromosphere its brilliant red colour. Further, there are the lines H and K of ionized calcium, which are very intense for photography (but not for the eye) and which characterize the highest level. The yellow line D_3 of helium is also one of the brightest; it appears in the flash spectrum but is not present in absorption in the photosphere. It is well known that helium was actually

discovered in the sun during the eclipse of 1868, and it was not until twenty-seven years later that it was isolated by Ramsay from gases extracted from the mineral *cleveite*. Up to the present some thirty helium lines have been identified in spectra of the chromosphere and prominences, all of them belonging to the arc spectrum of this element except for the faint line 4686 A, which belongs to the spark spectrum.

The best conditions for studying the spectrum of the low and high chromosphere naturally occur during the brief moments of total eclipses, and much has already been achieved in this direction since it has been possible to use photography in conjunction with diffraction gratings. We shall revert to this in the chapter on eclipses, but in the meantime it may be stated that these spectra can also be examined in full sunlight by means of solar towers, special measures being taken to avoid as far as possible the diffused light around the sun.

Hale and Adams, using the 60-foot tower of the Mount Wilson Observatory, were the first to succeed by this method in photographing the spectrum of the reversing layer in full sunlight and in establishing the differences between this spectrum and that of the photosphere as regards the relative intensity of the lines and wavelengths. Most of the lines, as already stated, show double reversal, the components sometimes being symmetrical with respect to the dark central component and sometimes asymmetrical, probably because of anomalous dispersion phenomena.

The enhanced lines all prove to be of exceptional intensity, and therefore they are observed as reversed lines sooner and more easily than the others. These lines belong chiefly to zirconium, caesium, lanthanum, praseodymium and neodymium, all in the first stage of ionization. Which of these high-excitation lines are the first to be observed in emission under the conditions mentioned, depends on the states of temperature and pressure in which the atoms of these elements happen to be at that particular level of the solar atmosphere, as has recently been explained by the theory of ionization and by the study of the equilibrium of the chromosphere under the action of the various forces to which it is subjected.

We have seen how Rowland, in order to determine the

intensity of the lines (page 86), adopted an empirical scale from 1000, the maximum number representing the intensity of the H line of ionized *Ca*, down to the -4 intensity of the faintest lines visible on Rowland's map and in recent photographs of the solar spectrum obtained with the most powerful spectrographs. The importance of knowing the exact intensities of the various Fraunhofer lines has increased with the progress of the atomic theory. Besides the intensity we must also measure what is termed the "profile" of the line; in other words, we ascertain by means of the micro-photometer how and in what quantity light is absorbed in the region of the spectrum occupied by the line proper. This is of great importance, since it enables us to determine the actual number of atoms excited in order to produce a line of a given intensity.

The mathematical theory of the formation of Fraunhofer lines leads us to expect that lines formed at different levels in the solar atmosphere will have different types of profile; for example, a line formed deep in the photosphere is expected to show a shallow profile, with a higher true central intensity than a line with the same equivalent breadth formed higher up in the solar atmosphere. As yet, we have hardly reached a point at which this prediction can be tested in detail on the profiles of solar lines of Rowland intensity less than 10, but an effect of this kind is seen when the apparent central intensities of the lines are plotted against their equivalent breadths.

Molecular lines, due to *CH* and *CN*, stand out as having higher central intensities, for a given equivalent breadth, than metallic lines. The figures given by Woolley suffice to show that the theoretical prediction is fulfilled, since the molecular lines are formed lower down in the solar atmosphere than the metallic lines. Methods of assigning depths in the solar atmosphere to individual lines from observations of their profiles will certainly develop with further improvements in photometric technique.

Righini, at the Arcetri solar tower, determined the intensity of 100 lines in the region 5288 A–5472 A of the solar spectrum both at the centre of the disc and at the limb. He confirms the characteristics of the spectrum at the limb which had already been pointed out by Hale and Adams, and shows how in the limb spectrum the excitation of the atomic levels is checked,

and this increases at levels of greater energy. In a later investigation Abetti and Castelli determined the central intensity of about 100 Fraunhofer lines of neutral and ionized atoms and cyanogen bands in the region 3750 A–3940 A, both at the centre and at the equatorial and polar limbs. From a discussion of the results it is found that the level at which the ionized atoms are formed is deeper than that of other lines. The central intensities increase with the excitation potential and are a maximum for lines of ionized elements and for the *CN* bands, and further the differences between the centre and the limb also increase in the same way. In addition a systematic difference is apparent between the observed intensities at the equatorial and polar limbs, which is probably related to the greater height of the chromosphere at the poles and to the difference of temperature between the equator and the poles, in accordance with the latest solar theories.

The most extensive measurements carried out so far of the equivalent breadths of Fraunhofer lines are those by Mulders at Utrecht. He examined 462 lines at the centre of the disc, distributed in eight different parts of the spectrum between 3900 A and 8600 A, and found that the equivalent breadth corresponding to a certain Rowland intensity does not remain a constant for different wavelengths. There are two maxima at 5200 A and 5500 A, and two minima at 5350 A and 5900 A; in the second minimum the equivalent breadths are reduced to about a third of their values at 5500 A, while at 8600 A the equivalent breadth for a given Rowland intensity is about five times as much as in the minimum at 5900 A. With the calibration curves obtained, Mulders also determined the total energy which has disappeared from the continuous spectrum in the formation of the Fraunhofer lines, as a function of wavelength.

The differences between Abbot's curve of the mean energy distribution in the solar spectrum, and the measurements of Plaskett and Fabry in the continuous spectrum, are shown to be wholly due to the absorption of the Fraunhofer lines. By accounting for this absorption the energy distribution in the continuous spectrum of the centre of the sun's disc is obtained from these measurements, and is found to differ notably from the black body curve.

Monochromatic Photographs of the Sun—Flocculi—Prominences Projected on the Disc

We have already stated (page 45) how monochromatic photographs of the sun in the various radiations can be obtained by means of the spectroheliograph. We have also pointed out that, when viewing the $H\alpha$ line at the solar limb with a spectroscope of sufficient dispersion, we can observe the phenomenon of double reversal, and that on receding a few seconds of arc from the limb the line appears singly reversed. Also in very active regions, as for instance disturbed regions in the neighbourhood of sunspots or on faculae, the line $H\alpha$, as first observed by Donati and Young, may appear with single or double reversal. The same phenomenon is also observed in other intense lines of the spectrum, particularly in the H and K lines of calcium, but these lines being situated at the extreme violet ends of the spectrum, observation can more conveniently be effected photographically.

If we photograph the sun with Deslandres' *spectro-enregistreur des vitesses* (page 51), viz. with a spectroheliograph whose second slit is broadened in such a manner as to include not only the line to be examined, for example K, but also a small region of the continuous spectrum around it—the region of the sun examined being given a discontinuous movement in such a way that the image of the solar disc is traversed—we obtain a representation of this image as depicted in Fig. 47. Here we see, in each of the exposures separated from the adjacent ones by a black line, the K line which, in the various regions of the solar disc, is a reversal which may be brighter or less bright than the continuous spectrum.

From this representation we at once pass to that obtained with the spectroheliograph by narrowing the second slit so that only the radiations emitted by the line under examination are seen, and by giving the spectroheliograph a continuous motion with respect to the entire solar disc. In this way we obtain spectroheliograms, usually with the lines K and H of calcium and $H\alpha$ of hydrogen, but also with other lines, provided they are sufficiently wide to ensure that only the radiation coming from the line itself affects the film.

In these spectroheliograms we see the sun's surface covered

by minute clouds called "flocculi," alternately bright and dark, consisting for instance of calcium or hydrogen, with a diameter of about one second of arc and resembling the granulation of the photosphere.

According to Langley's hypothesis, the "grains" into which

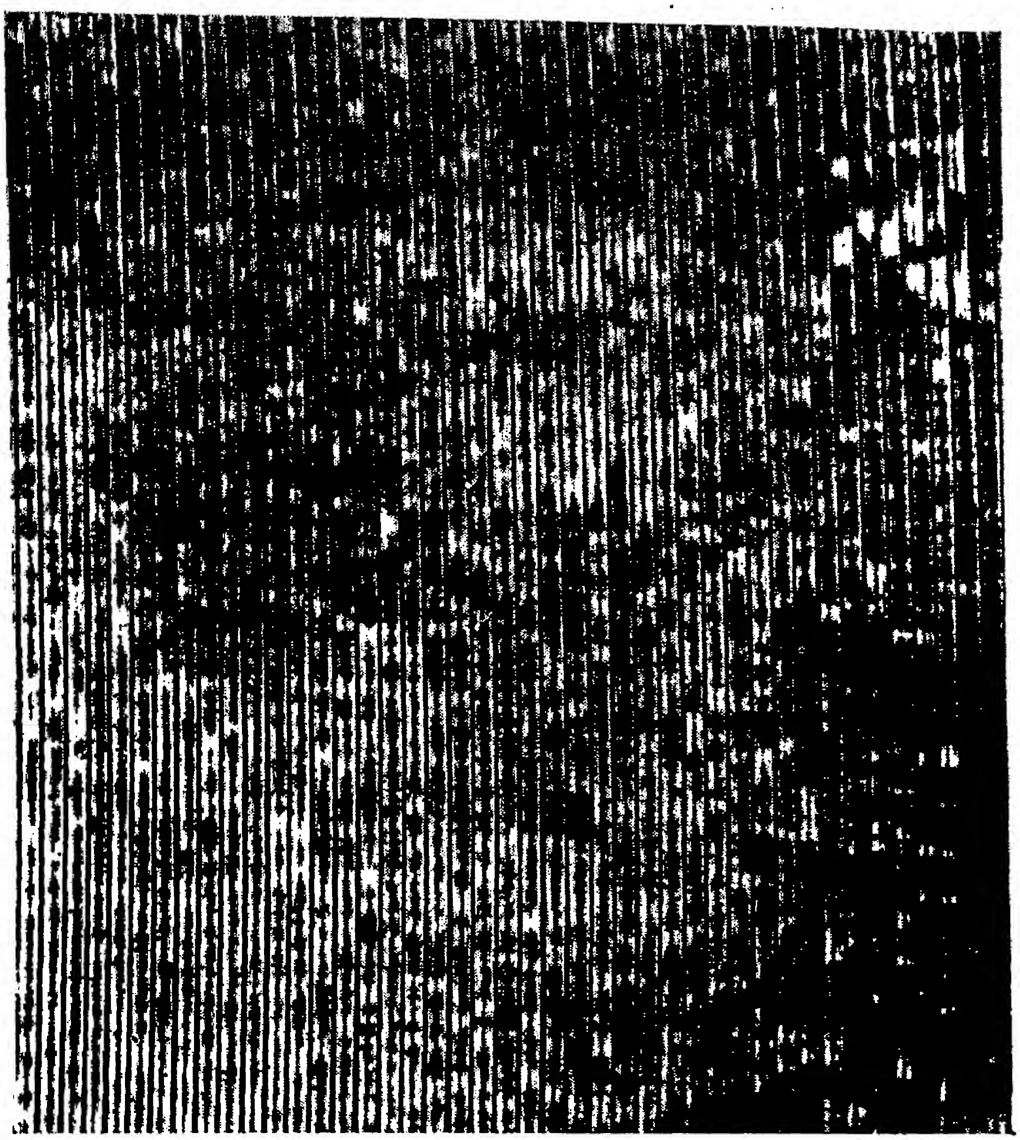

FIG. 47.—The K line photographed with the *spectro-enregistreur des vitesses* on a portion of the solar disc (Deslandres).

the photosphere is resolved when atmospheric conditions are favourable, would be the ends of columns of vapour protruding from the innermost layers of the sun. These "grains" seem to characterize regions in which convection currents from the sun's interior carry hot vapours to a height at which the temperature becomes so low as to cause condensation.

Hale is of opinion that in the highest part of these con-

densed columns other vapours offering greater resistance to condensation continue to rise, and that the granulation visible

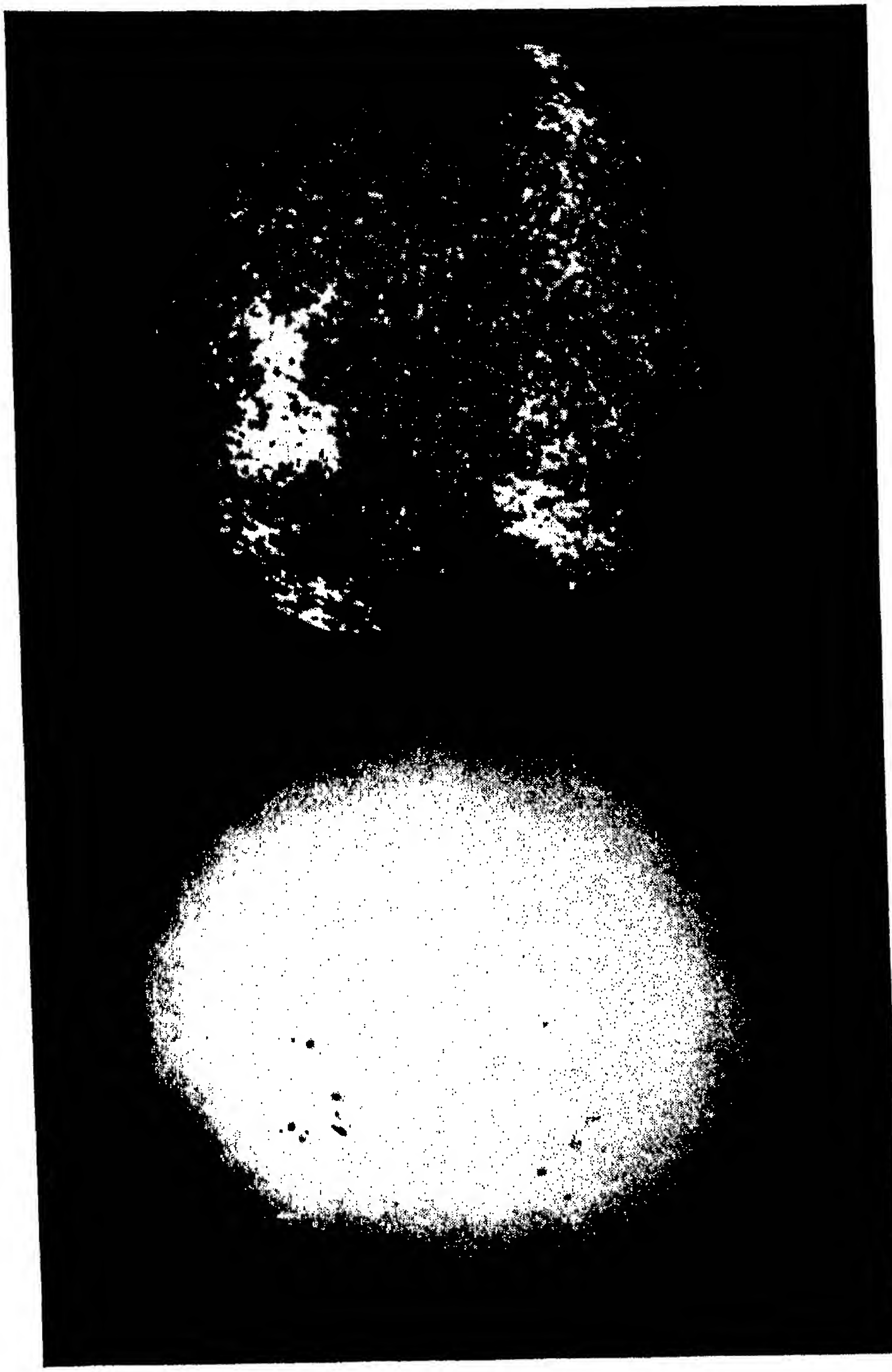

FIG. 48. Direct image of the sun and simultaneous spectroheliogram in calcium light (K line) obtained at Mount Wilson on January 11, 1926.

with the spectroheliograph may represent ascending calcium columns. It is, moreover, conceivable that the higher and more extensive clouds of calcium are due to those very same

clouds of vapour rising above the chromosphere in the form of jets or streamers, called "prominences" when observed at

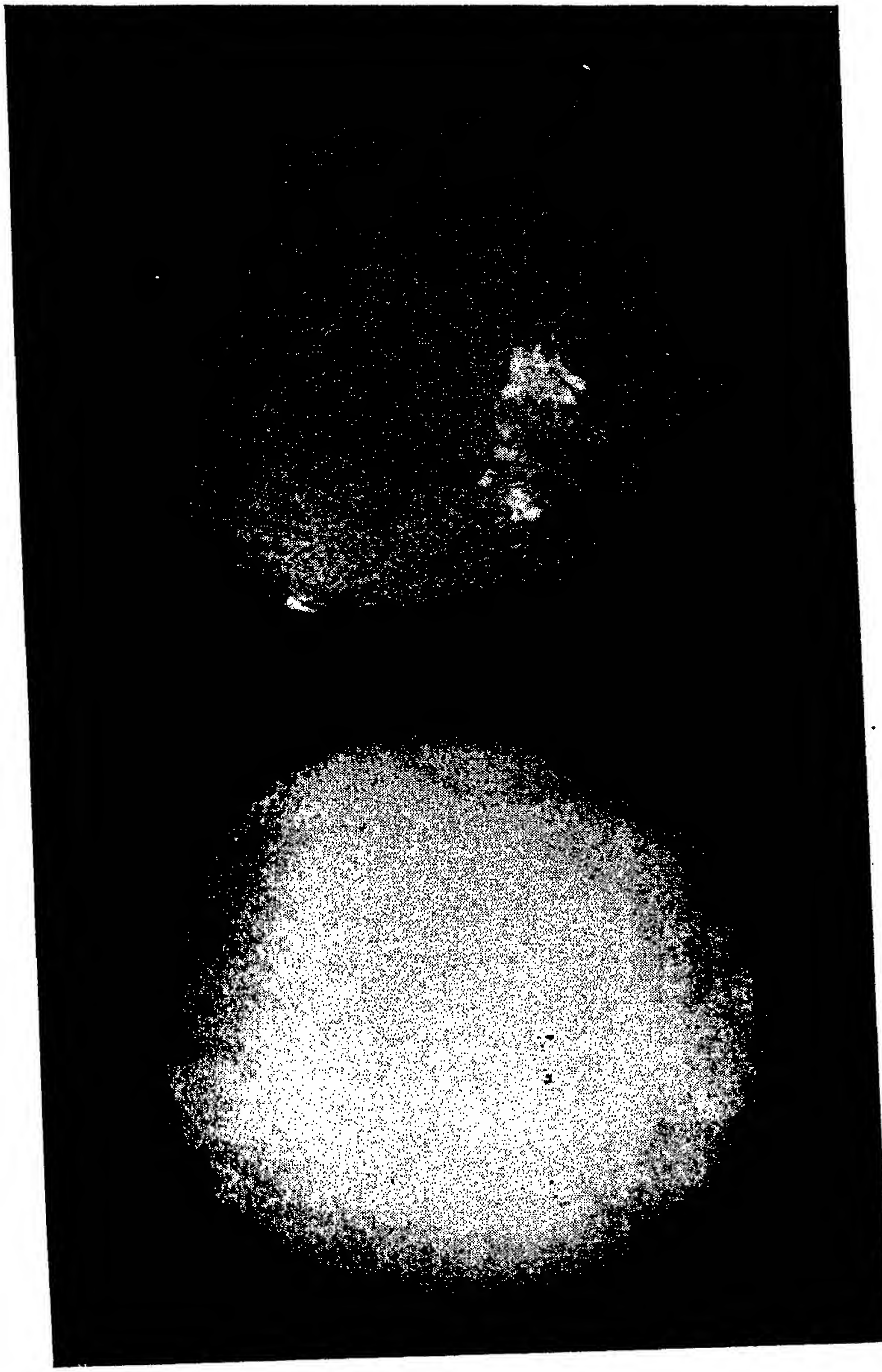

FIG. 49. Direct image of the sun and simultaneous spectroheliogram in hydrogen light (*H*α line) obtained at Mount Wilson on June 16, 1926.

the limb; these, as we shall see, are largely formed by calcium and hydrogen.

We have spoken of faculae, viz. of those luminous regions

visible near the solar limb which are above the ordinary level of the photosphere. It first seemed as if the clouds of calcium coincided with faculae, but it was soon found that a considerable difference exists between the calcium clouds and faculae, thus warranting the use of different names. As these clouds present the same appearance as flocculi they were thus termed by Hale and are nowadays generally known by that name. The spectroheliograph provides a means of analysing them and of determining in the following manner their structure at various heights above the photosphere.

We must suppose that at the base of the flocculi the calcium

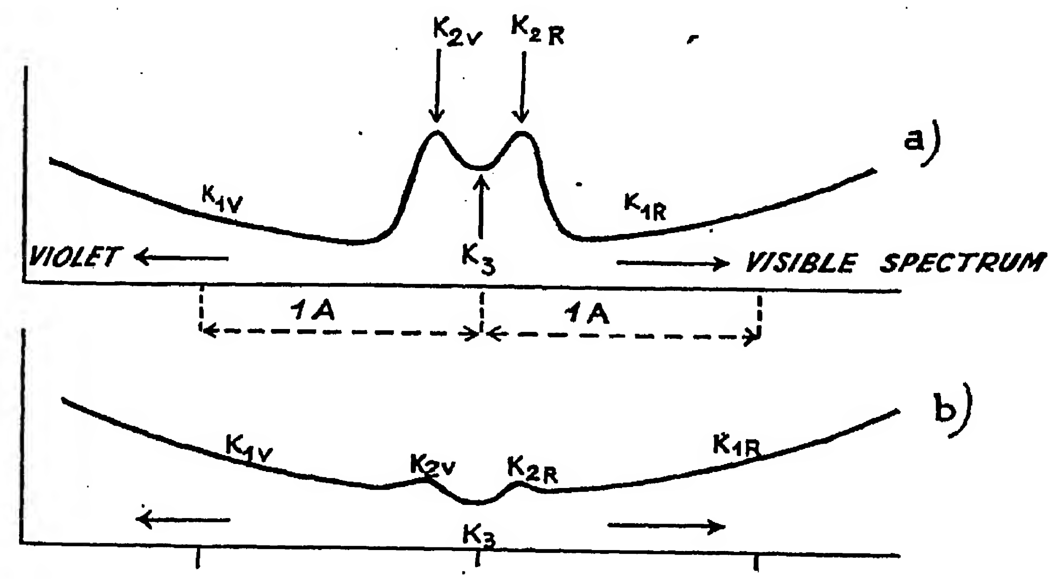

FIG. 50. Various parts of the K line of calcium.

vapour from the sun's interior is comparatively dense, whilst at greater heights it expands and becomes less dense. On the other hand, we know from laboratory experiments that the very dense vapour of calcium produces very wide spectral lines and that these lines become thinner and more sharply defined as the calcium vapour diminishes in density.

An examination of the H and K lines of ionized calcium tells us that on the sun this vapour is in very variable conditions of density. We will confine our attention to the K line, because the H line is very close to the $H\epsilon$ line of hydrogen and can only be isolated from the latter with large dispersion, but what is true for K will also hold good for H and for other intense lines of the solar spectrum, such as $H\alpha$, $H\beta$, etc.

In its entirety the wide absorption line K is generally indicated as K_1 (Fig. 50), and we shall be able to distinguish in it

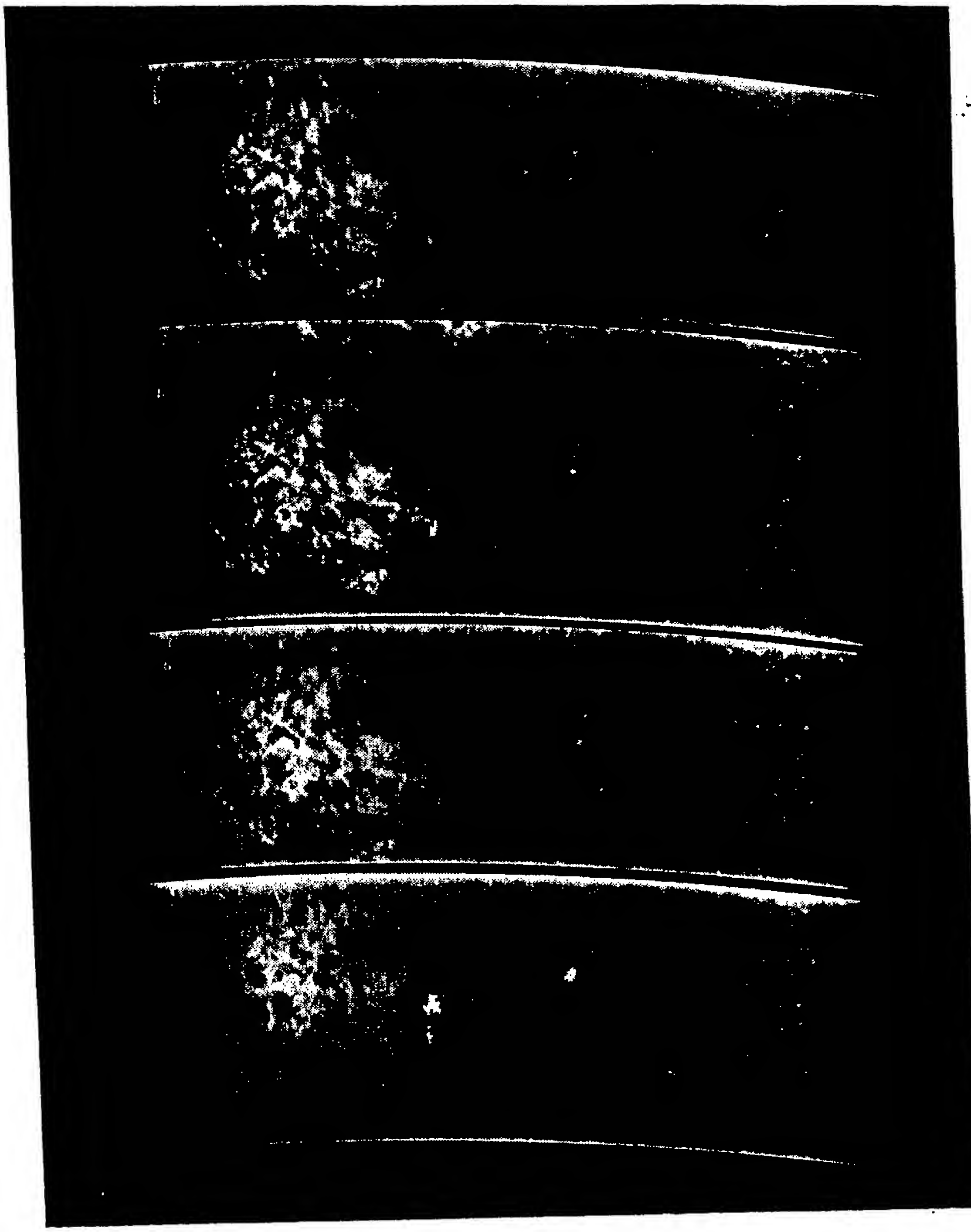

FIG. 51. Spectroheliograms obtained at the Yerkes Observatory (August 22, 1919) which approach nearer and nearer (from bottom to top) to the centre of line K.

the violet part K_{1v} and in the red part K_{1r}. As explained above, this whole line is due to the denser calcium vapour at low level.

When we examine the same line at the solar limb or above

the flocculi, or in general over a disturbed region of the sun, we find single or double reversal. When there is single reversal we indicate the central line of light as K_2; when there is double reversal we distinguish the two components K_{2v} and K_{2r}, and in the centre the absorption line K_3. In reality the line or the components K_2 also exist in the undisturbed regions of the disc, but they are very faint. Now it is at once evident

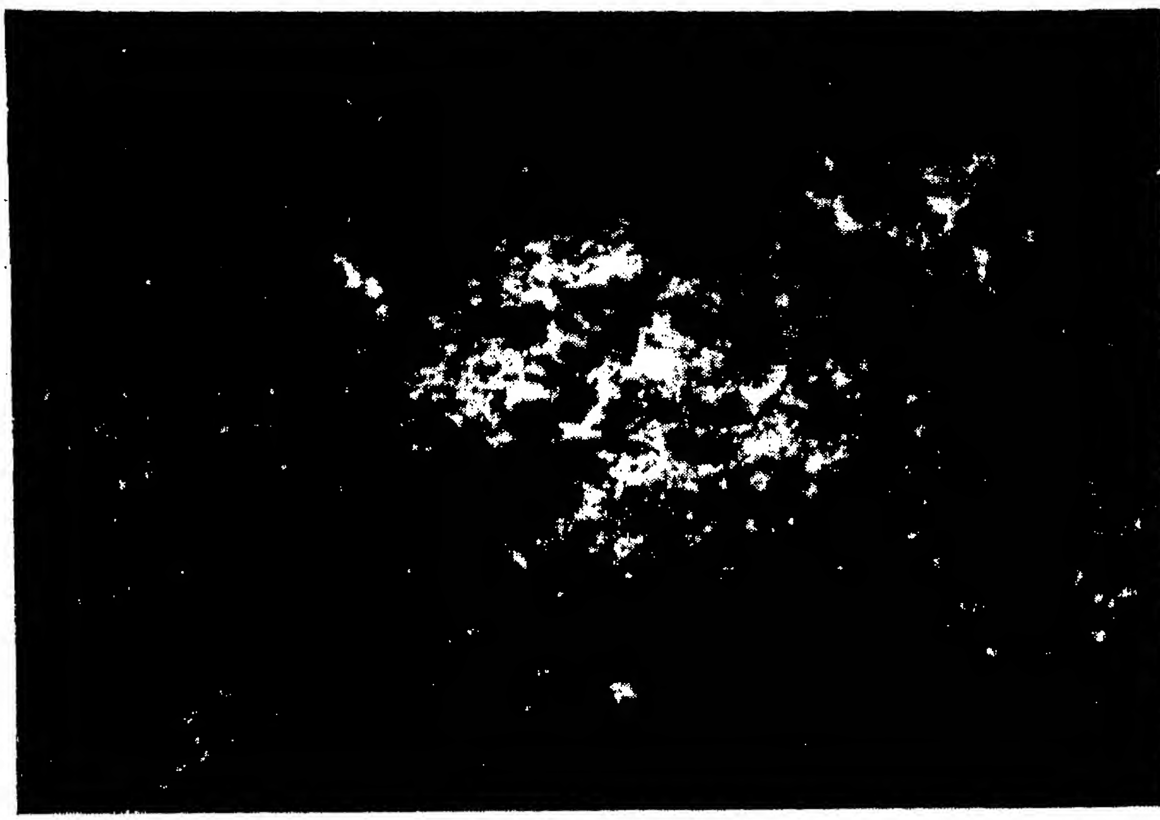

FIG. 52. Group of spots photographed at the Yerkes Observatory, with line K_3, August 20, 1919.

that the vapour giving rise to the components K_2 is higher and less dense than that which produces the line K_1 and that which produces the line K_3 is also higher and less dense than the vapour giving rise to the K_2.

The spectroheliograph offers the possibility of separating and photographing these various levels of calcium vapour. It is sufficient to point the second slit near the edge of the wide line K_1 and to photograph the solar disc with it in order to obtain the distribution of that part of the vapour which is so dense as to produce the line of that breadth. No light at all of the rarefied higher vapours can under these circumstances enter the second slit, because this light is incapable of

penetrating the second slit when placed in that particular position. Flocculi thus obtained are almost identical with faculae.

According as the second slit is brought nearer to the centre

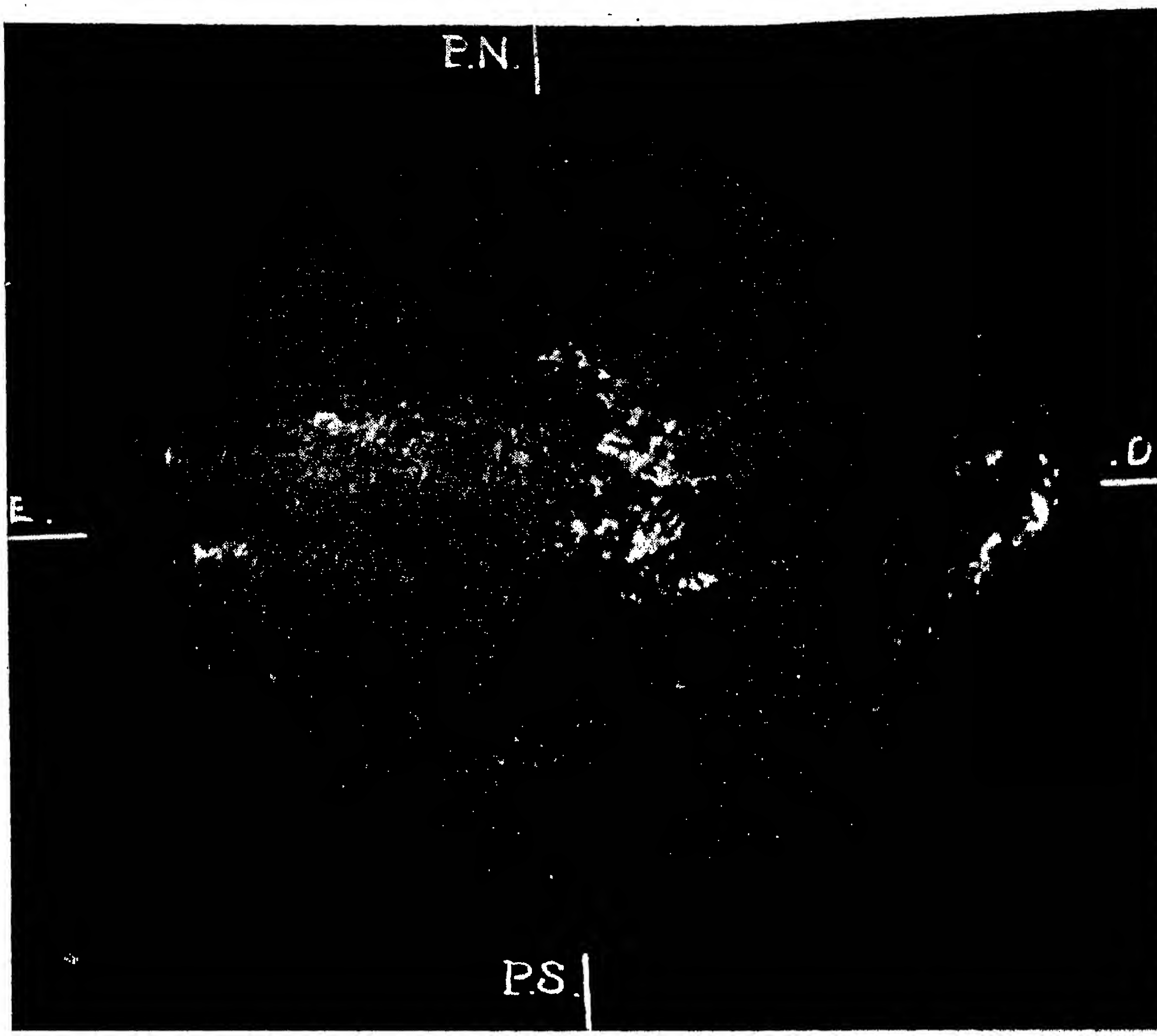

FIG. 53.—Spectroheliograms obtained with line $H\alpha_{2.3}$ at Meudon, December 17, 1929.

of the K line, pointing successively to K_{2v}, to K_{2r} or to K_3, increasingly high layers are photographed as shown in the examples reproduced here (Figs. 51 and 52). Flocculi acquire an appearance quite peculiar to themselves and differ from faculae to an increasing extent. It is seen that flocculi at the higher levels always cover the greater part of the groups of spots, and if in conjunction with the spectroheliograph we

also use the *spectro-enregistreur des vitesses*, it will be possible to ascertain the velocity of motion of the vapours and their circulation on the spots themselves.

The intensity of flocculi may be more or less pronounced according to the state of excitation of the vapour which pro-

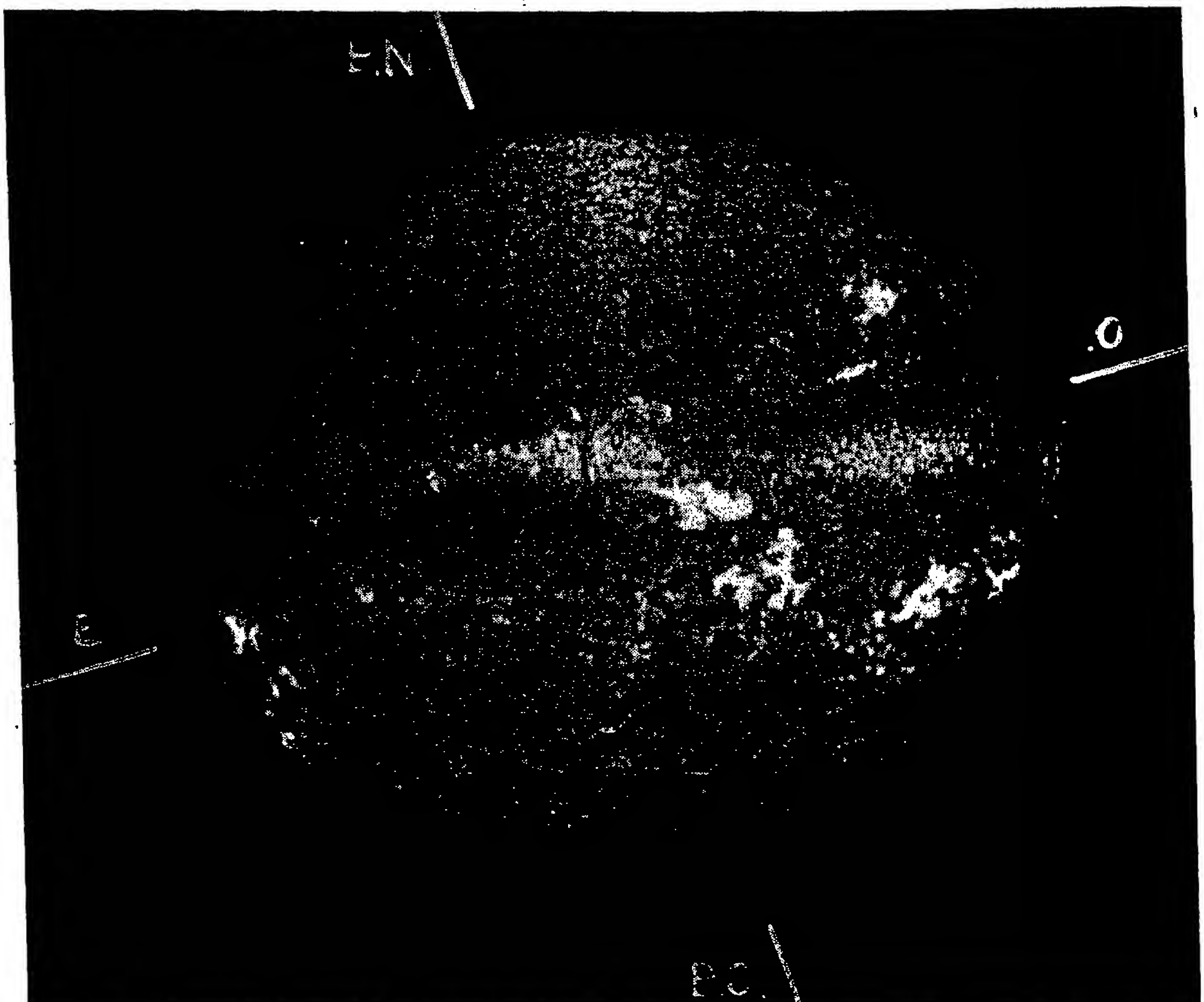

FIG. 54. Spectroheliograms obtained with line $H\alpha_{2,3}$ at Meudon, August 17, 1929, with dark filaments.

duces them; sometimes, in very disturbed regions, their intensity is very great; in these cases the vapour is erupted from the sun's interior at a great velocity, and rapid changes are clearly observable with the spectrohelioscope, whereas ordinary flocculi of medium intensity change slowly and represent less disturbed regions of the sun's surface.

Flocculi are closely associated, if not identical, with the

phenomena known as prominences which are observed at the solar limb; a still closer relation would seem to exist between prominences and the particular class of flocculi which, owing to their peculiar appearance, are said to be "dark" or are

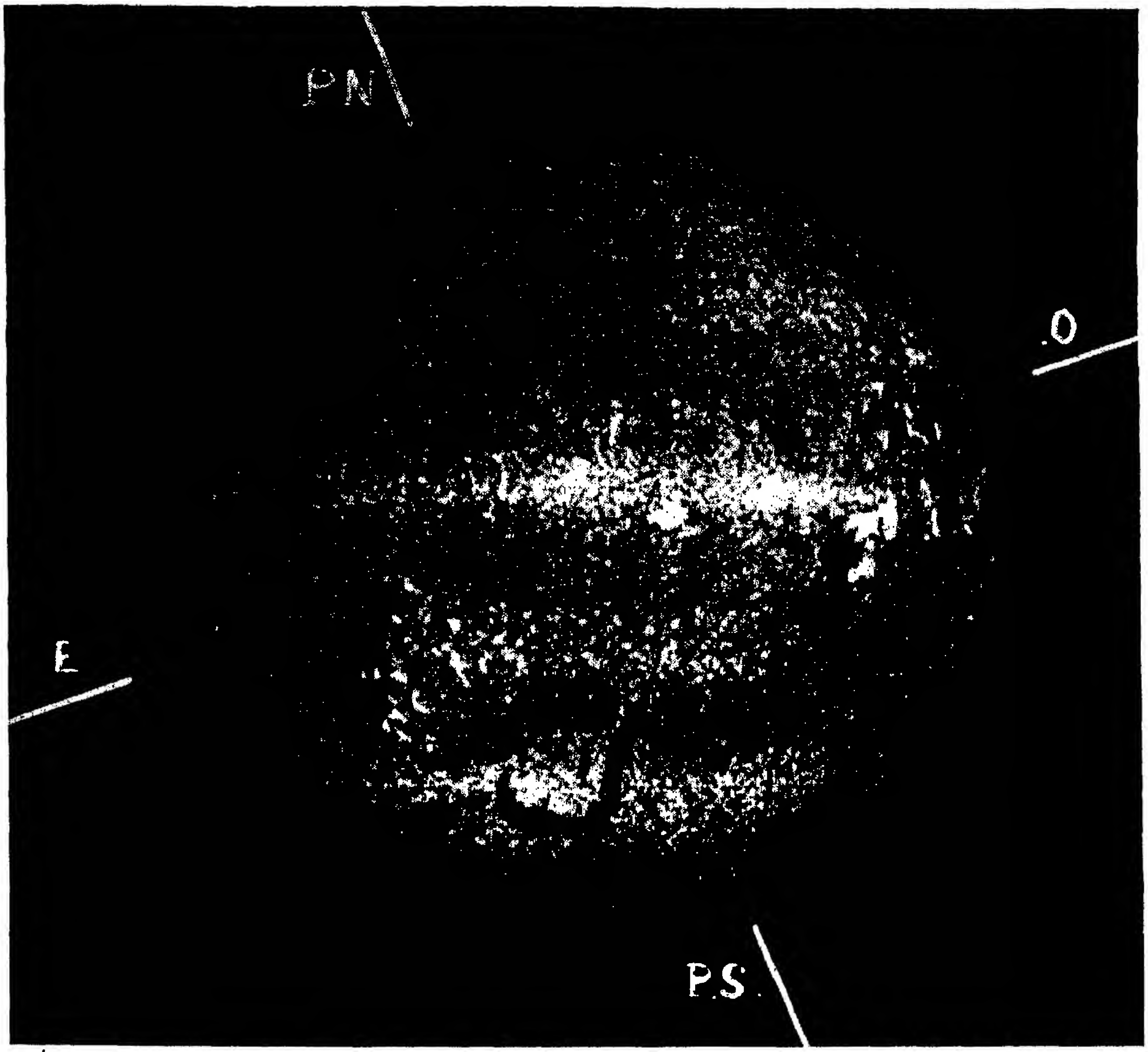

FIG. 55. Spectroheliograms obtained with line $H\alpha_{2,3}$ at Meudon on August 31, 1929, with a large filament or prominence projected on the disc.

described as "filaments." These flocculi are only obtained when the slit of the spectroheliograph is pointed to the line K_3 in such a manner that only light emitted from this line can traverse this slit. Since line K_3 is narrow compared with the other components, it follows that very large dispersion of the spectroheliograph is necessary in order that this line may be sufficiently broad to permit light to pass in sufficient quantity

to impress the photographic film. This is achieved with the multiple spectroheliograph used at Meudon, in which large dispersion is obtained, with elimination of diffused light, by the use of successive dispersing apparatus.

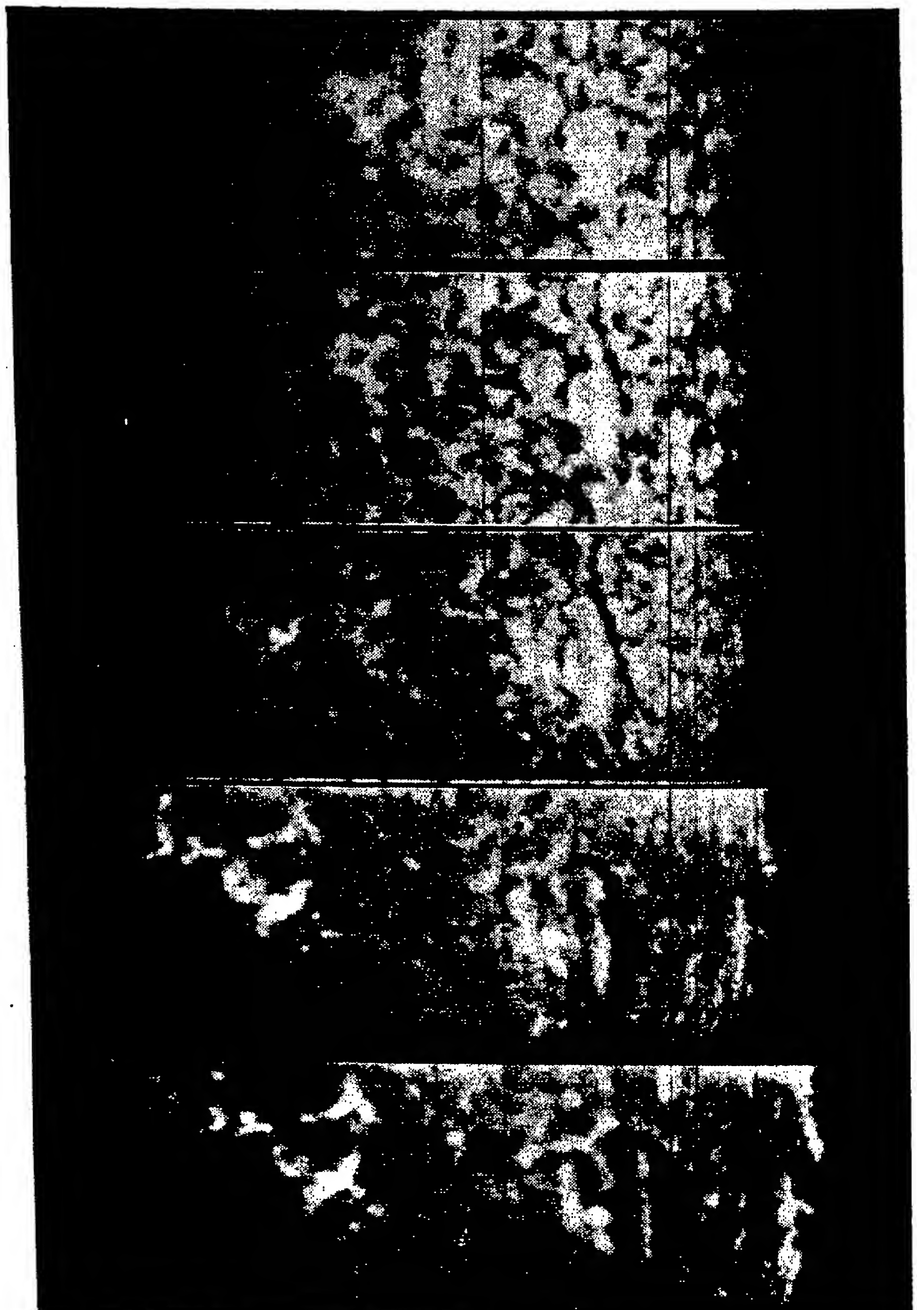

FIG. 56. Series of spectroheliograms obtained at Mount Wilson by moving the slit 0·33 A towards the red from the centre of the *Hα* line (from bottom to top in the figure).

These images in the monochromatic light of K_3 present not only the appearance described, but also show very distinct long black lines which are curved more or less with respect

to the solar parallels constituting the dark flocculi or filaments. When these flocculi are brought into the solar limb as a result of the sun's rotation, the presence of a prominence is nearly always observed at the point where the filament ascends or descends, and hence it must be concluded that filaments are nothing else but prominences projected on the disc.

Up to now we have only considered the K line; the same may be said of line H, except for the perturbations caused by the next line $H\epsilon$, but if we take the hydrogen lines the appearances obtained are different, especially in the line $H\alpha$, for which we must naturally use red-sensitive films. Also on spectroheliograms made with these lines we see bright and dark flocculi, but the general structure of the floccular network and of the flocculi themselves shows considerable differences, as can be seen from Fig. 53 and subsequent figures.

Spectroheliograms taken with the $H\alpha$ line show the finer and more detailed structure in regard to the high layer of the solar atmosphere, which is isolated with this line. According as we use the one or the other part of this line, we obtain, as in the case of line K, images of the various levels. At the centre of line $H\alpha$, which in analogy with line K_3 is called $H\alpha_3$, we find flocculi differing considerably from those obtained with the edges of the line. In this case, too, there are dark filaments; the differences between the flocculi of calcium in K_3 and those of hydrogen in $H\alpha$ are shown in the figures reproduced here. The disturbed regions are generally the same, but the structure, relative intensity and configuration of the flocculi show considerable differences.

Another characteristic appearance of spectroheliograms taken with the $H\alpha$ line is that obtained by Hale, viz. the cyclonic or vortex structure of those flocculi which are in the neighbourhood of sunspots and which, as we shall see later, led to the discovery of magnetic fields on the spots themselves.

These solar "vortices" may be observed on a single spot and show a very regular distribution, or else they are associated with groups of spots and are then of more complex structure. The appearance of the well-defined and simple vortices is such that it indicates a right-handed rotation of the vapours in the southern hemisphere, and a left-handed rotation in the northern hemisphere, it being assumed that the direction of

motion is towards the interior of the spot. Nevertheless, it cannot be stated that this is a general law corresponding to that of terrestrial cyclones, because in many cases there are spots close together in the same hemisphere and often belonging

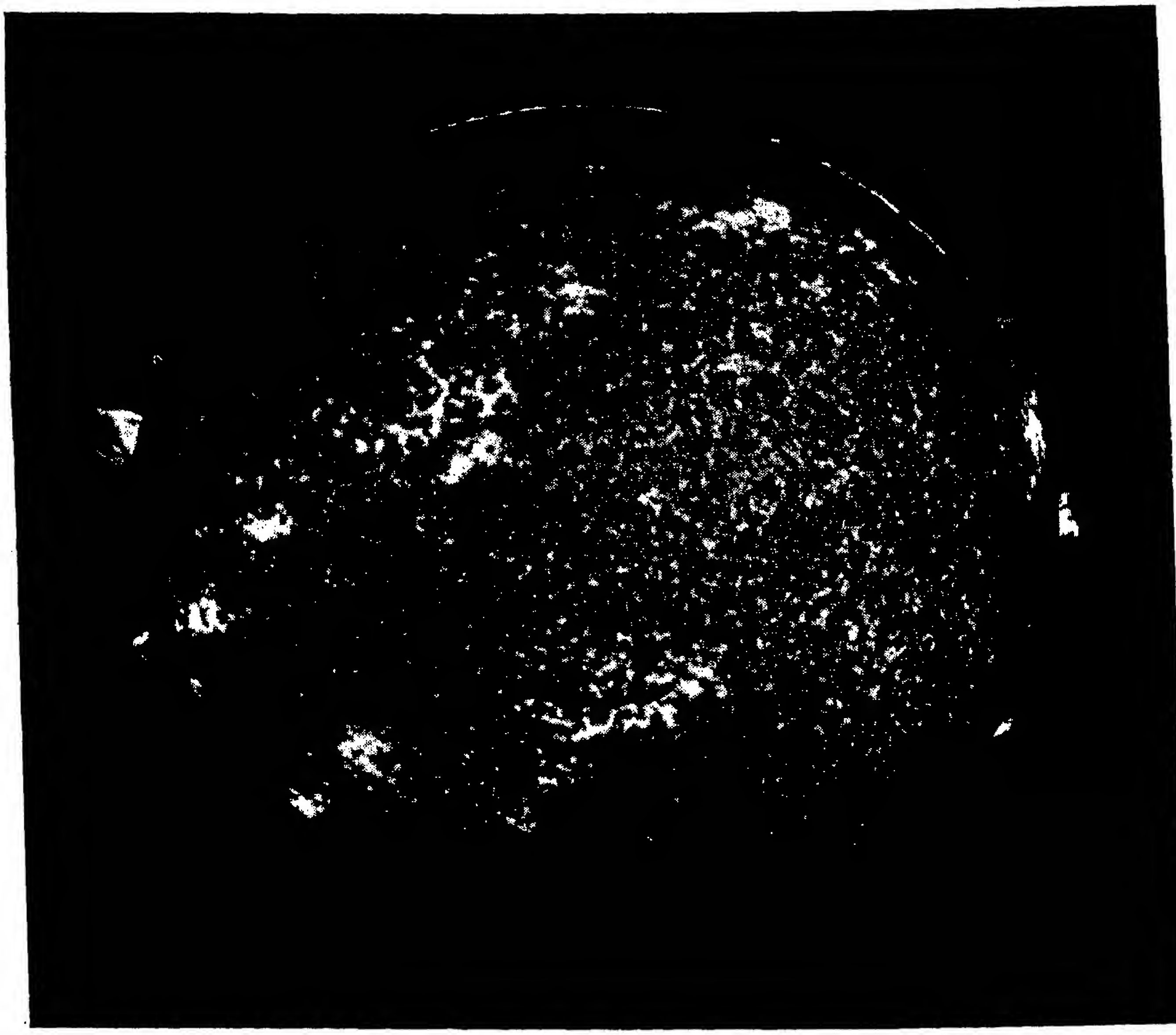

FIG. 57. Spectroheliogram in light of the K line of calcium combined with prominences photographed at the solar limb (Mount Wilson, May 22, 1916).

to the same group, which show vortices moving in opposite directions.

In some cases these vortices seem to exercise a strong attraction on the surrounding gases. Thus, St. John photographed with the spectroheliograph a long dark filament in the neighbourhood of a well-defined vortex which had its centre on a spot. The nucleus of the spot resolved itself into two parts, and within a few hours, in successive spectroheliograms taken

with the $H\alpha$ line, the filament not only spread to the spot but actually reached it, dividing into two branches each of which touched the two nuclei, as if these constituted centres of attraction. The mean velocity of motion of the filament towards the spot exceeded 100 km per second.

For observations of this kind the following application of the spectrohelioscope invented by Hale is appropriate. When a flocculus or filament is moving at considerable velocity along the line of sight, on account of the *Doppler effect* it can no longer be observed in the wavelength of the line $H\alpha$ to which

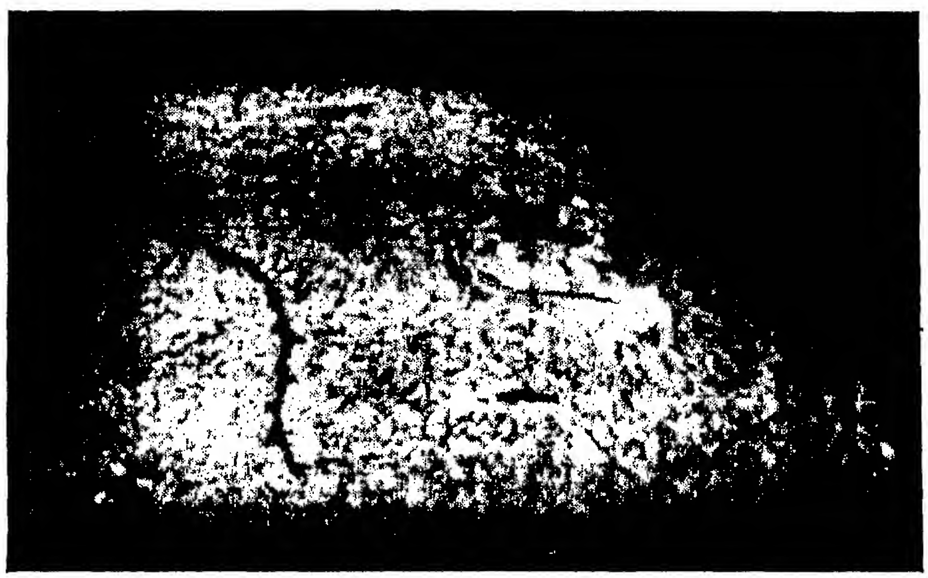

FIG. 58. Hydrogen filament photographed at Arcetri on March 22, 1927.

it belongs but, if the velocity of recession or approach is greater than about 30 km per second, the line in question will no longer be passed by in the second slit of the spectroheliograph and hence it will no longer be visible. The $H\alpha$ line may be led back into the second slit by inserting in the path of the rays a glass plate with a plane parallel surface, which, when suitably inclined, produces a shift of the spectrum in the focal plane. This shift is measured by the angle of inclination of the plate to the beam emerging from the grating or from prisms, and from measurement of this angle we deduce the velocity of the filament along the line of sight.

With this method, too, we obtain the same results as with Deslandres' *spectro-enregistreur des vitesses*, with the advantage that the various phases of a given phenomenon can be followed

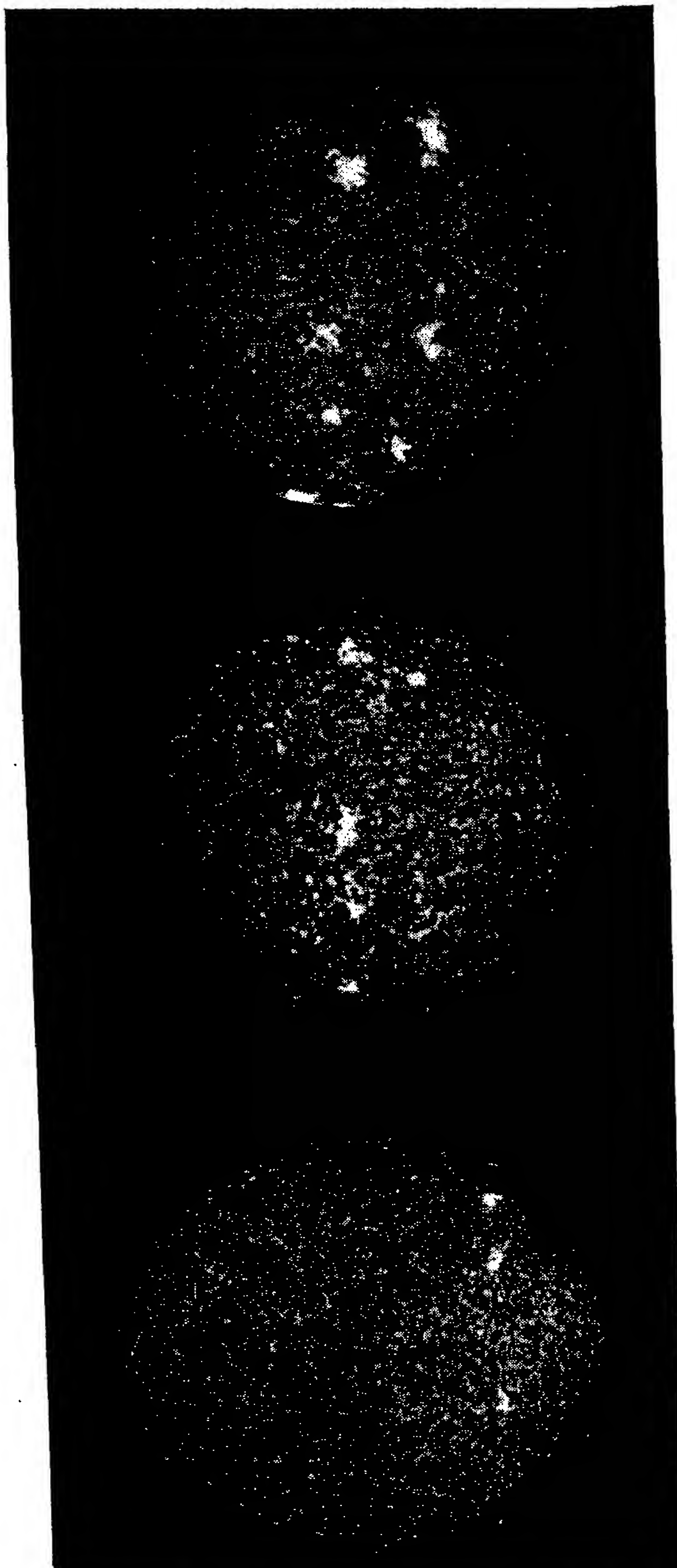

Fig. 59. Spectroheliograms in light of the calcium line K_2. Characteristic numbers 0, 1, 2 for calcium flocculi (Mount Wilson).

more rapidly. In this way Hale studied several hydrogen eruptions which occurred at the last maximum period, generally in the neighbourhood of very active spots, and found that in the brilliant hydrogen masses the $H\alpha$ line is shifted from the violet part of the spectrum; so these eruptions correspond to hydrogen in motion towards the observer and hence in an ascending direction. The dark filaments, on the other hand, are observed from the red part of the $H\alpha$ line and are produced by absorption of the hydrogen masses moving away from the observer, viz. in a descending direction towards the centre of the sun.

The small filaments in the immediate vicinity of the spots may be considered as "bridges" placed above the chromosphere; one of their extremities generally commences at a spot and finishes in a small black circle situated on the outer border of the penumbra. The displacements of the vapour along the filament are always directed towards the spots, often with a high radial velocity ranging from 25 to 115 km per second. The shape of these filaments and their rapid variations would suggest that they are merely eruptive prominences (page 140) projected on the disc.

In addition to the calcium and hydrogen lines already mentioned there are other lines which have been systematically used with the spectroheliograph, especially by D'Azambuja at Meudon. These lines, numbering about ten, belong to five different elements: iron, calcium, magnesium, neutral sodium, ionized strontium. As in the case of ionized calcium, when the second slit is placed over the wings of one of the lines, we obtain a spectroheliogram which is almost identical with the direct image of the sun, and as the slit approaches the centre of the line, the flocculi are seen to appear, just as happens in the case of K_1. After a maximum of visibility, these regions and the bright flocculi disappear and the granular structure uniformly distributed over the entire disc stands out prominently. When the second slit is exactly placed over the centre of the line, the images show, together with a slight granulation, facular zones and bright flocculi, which seem to be identical with those obtained in K_1 but relatively less intense.

The granulation obtained with these lines is similar to that of hydrogen and conveys the same impression of being com-

FIG. 60.—Spectroheliograms in light of the calcium line K_2. Characteristic numbers 3, 4, 5 for calcium flocculi (Mount Wilson).

posed of dark grains on a bright background, the mean diameter of the grains being about five times that of the photospheric grains. There is no trace whatsoever of vortices in the regions of the spots.

The vortices would be due to mechanical influences analogous to those produced by our terrestrial cyclones, to which influences the high layers of the less dense and less viscous vapours would be more sensitive than the lower layers. These researches finally confirm the idea that the granulation constitutes the essential structure of all chromospheric vapours.

With regard to the comparison and duration of floccular zones, it may be stated in general that they last longer than the spots and usually commence with a small regular flocculus in a particular region. Subsequently the flocculus becomes longer, with a tendency towards a certain orientation, and entirely covers a more or less extensive zone in which one or more spots appear. These initial phases succeed each other rapidly in the course of a few days, and at the same time the zone continues to spread and remains compact. When it has attained its full development it remains stationary for a certain time and then begins to disperse, its area still increases, the spots disappear; the brighter parts gradually lose their brightness and the disturbed region finishes by resuming the ordinary aspect of the granulated chromosphere.

The orientation of floccular zones, when they have attained their normal elongation, is not haphazard. In each hemisphere the zones are inclined towards the equator so that their western extremity is nearer to it than their eastern extremity. The angles of inclination vary from 0° to 40°, without a clear-cut relation to the heliographic latitude. We have seen how the groups of spots show angles of inclination which, though analogous, are much smaller, attaining only 19°, and how, on the other hand, this angle increases regularly with latitude (page 80).

The instability of floccular zones follows that of sunspot zones; at the commencement of a new cycle they make their appearance at high latitudes, following the spots in their shift towards the equator. They attain a maximum of activity as regards area and intensity with the maximum of sunspots, and subsequently decrease until they nearly or entirely dis-

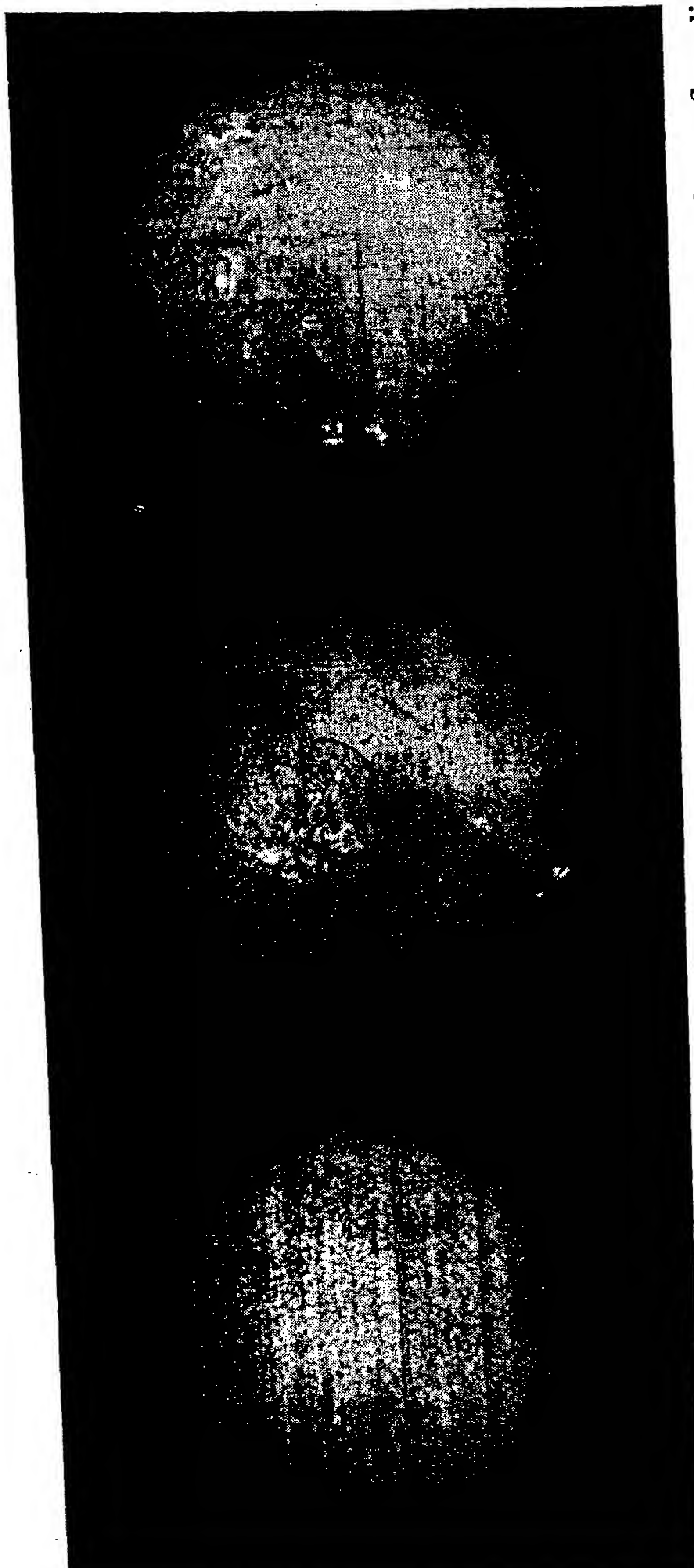

FIG. 61. Spectroheliograms in light of the *Hα* line. Characteristic numbers 0, 1, 2 for the bright hydrogen flocculi (Mount Wilson).

appear during the minimum sunspot period. The presence of flocculi is therefore another important indication of solar activity. The variation in floccular activity is followed by means of spectroheliographs and spectrohelioscopes all over the world, and it is possible to measure the area and intensity of the flocculi in various phases of the cycle. Since these measurements are rather lengthy and complicated, in order to gain more rapid information as to the state of solar activity in regard to the particular activity of the calcium and hydrogen atmosphere an empirical scale numbered from 0 to 5 has been established by international agreement, 0 in the scale being understood to mean the complete absence of flocculi and 5 the maximum area and intensity occurring during the maximum period of solar activity.

These characteristic numbers, or "character figures," as they are termed, are stated separately: (1) for calcium flocculi observed by using the central part of line K (K_2 and K_3), (2) for the bright flocculi of hydrogen, and (3) for the dark flocculi or filaments observed in line $H\alpha$ ($H\alpha_2$ and $H\alpha_3$) (Figs. 59 and 64).

The character figures judged by the eye from day to day on spectroheliograms are stated separately, not only for the entire disc but also for a central zone limited at the circular surface of half a diameter of the disc, and are collected by the various observatories; from the Zürich Observatory they are published under the auspices of The International Astronomical Union by W. Brunner in a quarterly bulletin (page 332).

Rotation Period of Flocculi

Flocculi of course also participate in the sun's rotation, and it is interesting to investigate whether they rotate at the same speed and are subject to the same law as sunspots. Several observers have carried out these measurements by trying to identify the same points of a particular flocculus in the course of its rotation, but it will be understood that, either because of the difficulty of identifying these points or because of the individual proper motions of the flocculi, these determinations do not furnish reliable and accurate results; nevertheless, the

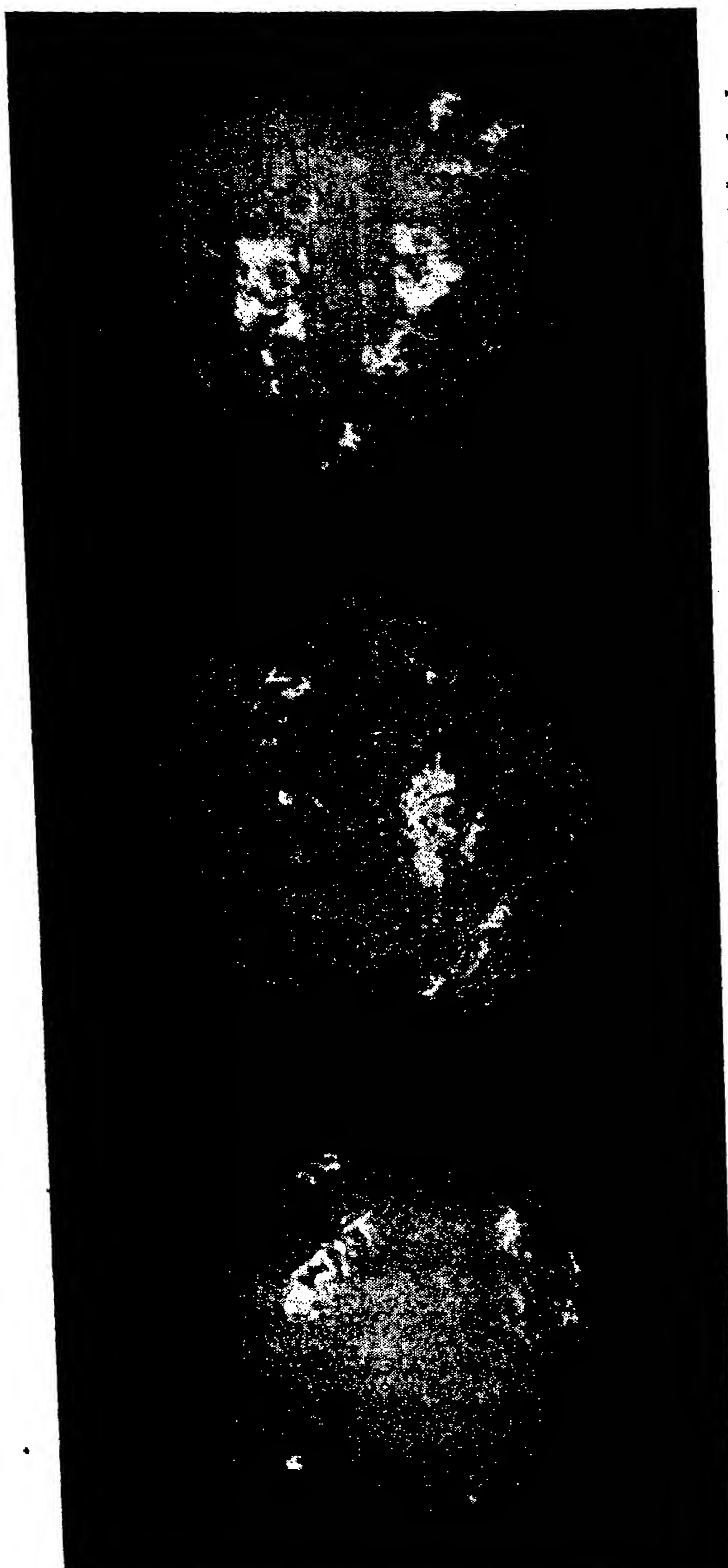

Fig. 62. Spectroheliograms in light of the $H\alpha$ line. Characteristic numbers 3, 4, 5 for the bright hydrogen flocculi (Mount Wilson).

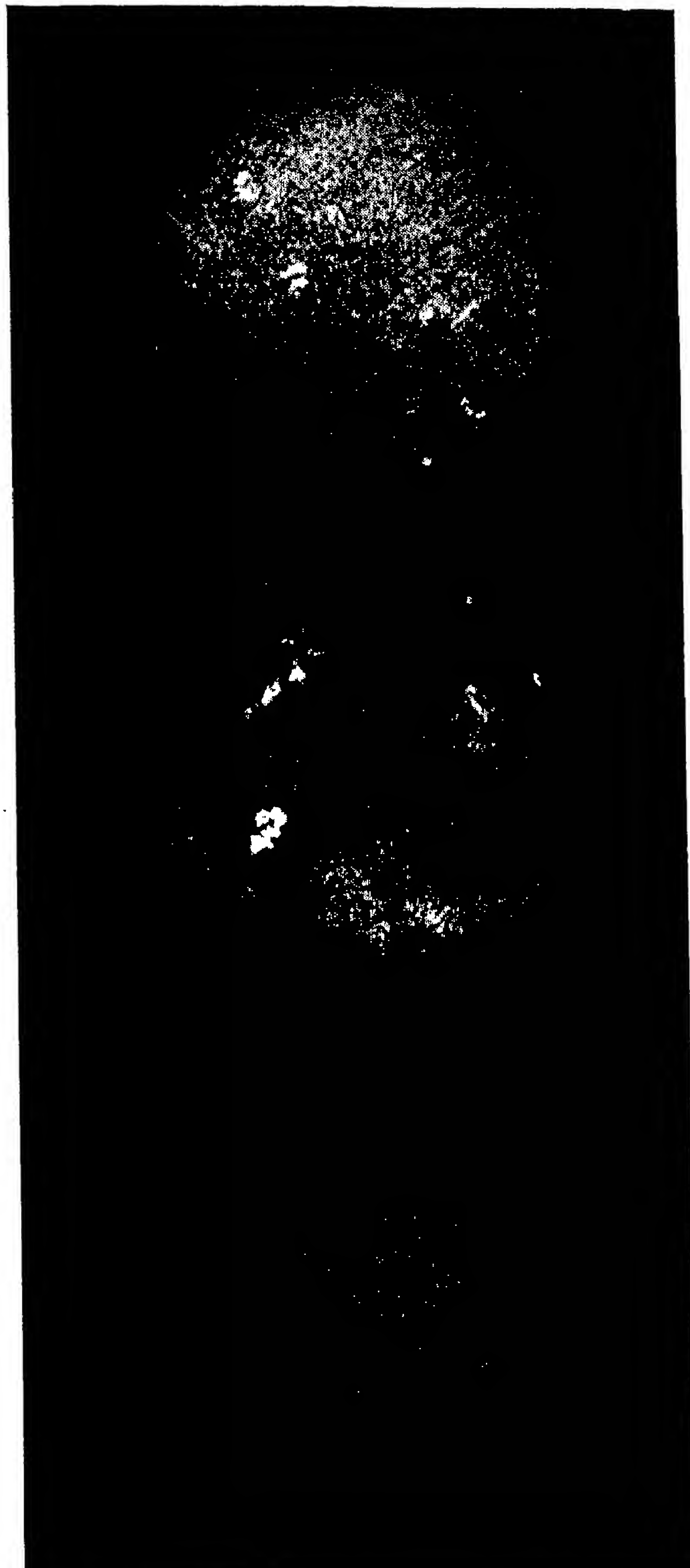

FIG. 63. Spectroheliograms in light of the *H*α line. Characteristic numbers 0, 1, 2 for the dark hydrogen flocculi (Mount Wilson).

FIG. 64. Spectroheliograms in light of the $H\alpha$ line. Characteristic numbers 3, 4, 5 for the dark hydrogen flocculi (Mount Wilson).

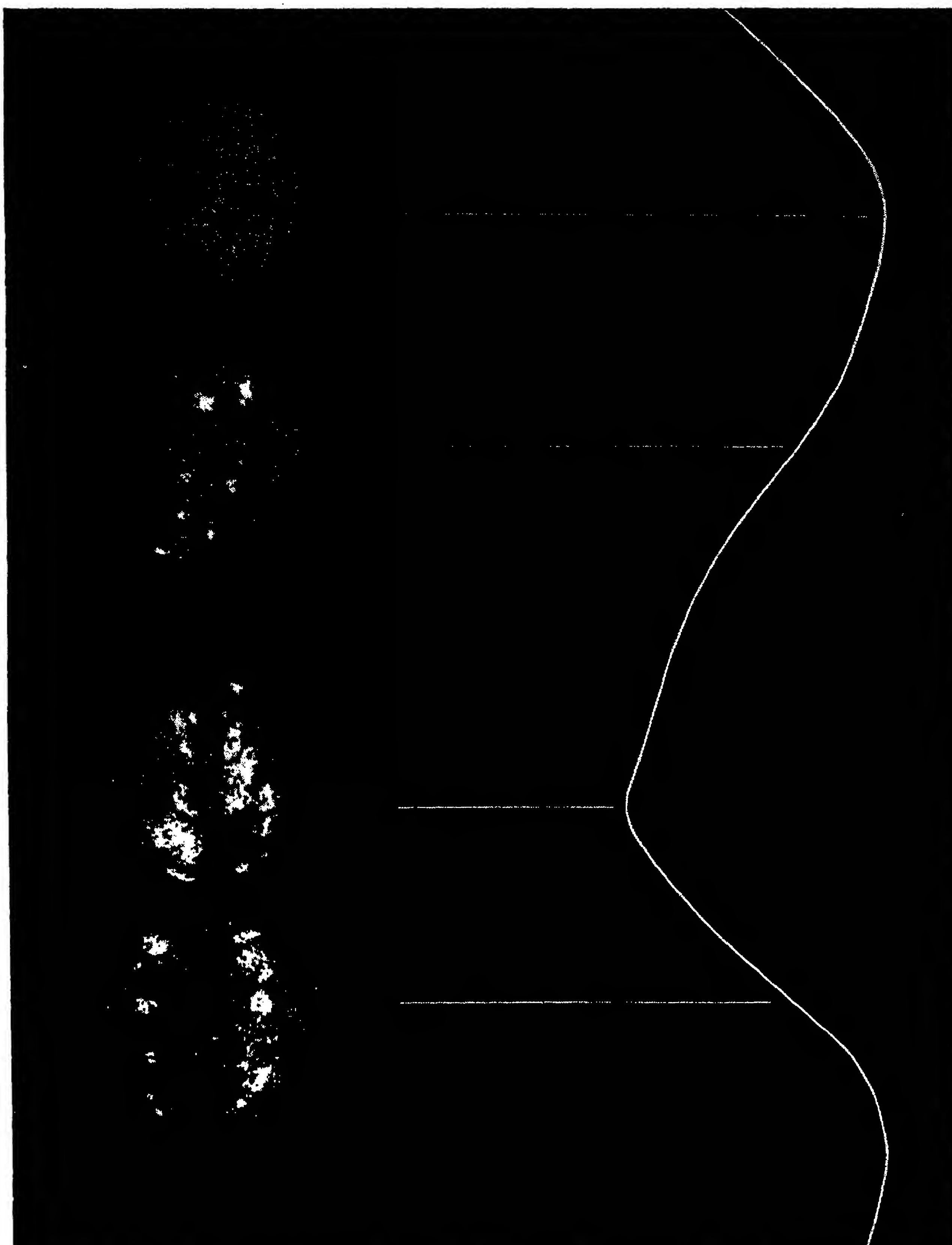

Fig. 65. Typical spectroheliograms of calcium flocculi, showing the variations in area and latitude during the various phases of the eleven-year cycle indicated by the curve (Mount Wilson).

agreement obtained in several series of measurements is satisfactory.

The most extensive measurements have been executed by Fox with the Rumford spectroheliograph attached to the 40-inch equatorial of the Yerkes Observatory. From 4000 points selected in the calcium flocculi on 285 plates, the diurnal sidereal motion was deduced, using in the great majority of cases two plates taken on successive dates. The results obtained are represented by Fox in an empirical formula similar to that found for the spots. Indicating by ξ the angle covered by the flocculi in one day, he obtains:

$$\xi = 11 \cdot 584^\circ + 2 \cdot 976^\circ \cos^2 \phi$$

From examination of the proper motions of these flocculi around the spots, Fox furthermore establishes the existence of a cyclonic movement similar to that which is evident in the flocculi of $H\alpha$.

The mean results of the various determinations for the period of solar rotation at the various latitudes, deduced from calcium flocculi, are as follows:

ϕ	ξ	ϕ	ξ
0°	14·53°	25°	14·07°
5	14·48	30	13·89
10	14·40	35	13·79
15	14·31	40	13·61
20	14·21	45	13·23

Comparing these results with those obtained for faculae and for spots, we find, as was to be expected, that the velocities given by faculae almost coincide with those deduced from calcium flocculi; the spots, on the other hand, give a period of rotation which, for all latitudes, is in the mean about 0·1° lower in ξ. We thus see, at any rate for these two phenomena of solar activity, the commencing delineation of a trend that agrees with the hypothesis of the various levels of the solar atmosphere, the highest levels being assumed to possess the swiftest movements.

Determinations of the rotational period by means of hydro-

gen flocculi are very scarce because of their very variable appearance, which renders the measurements uncertain. Nevertheless, those executed at Mount Wilson seem to show beyond all doubt that the rotational movements of hydrogen flocculi differ considerably from those of calcium flocculi and are indicative of a different law of rotation. These movements would not therefore represent an equatorial acceleration, but it may be presumed that the angular diurnal motion has a mean value that is equal for all zones:

$$\xi = 14 \cdot 6^\circ.$$

It is interesting to compare this result with that deduced by the spectroscopic method, as we shall do later (page 166), using the $H\alpha$ line.

From the observations effected at Kodaìkanal, Royds obtains the velocities of hydrogen flocculi with the dark filaments by measuring the distance from the central meridian of those parts of the filament which could be identified during successive days. The results show rather large variations, but in the mean he finds:

$$\xi = 14 \cdot 8^\circ$$

which confirms the fact that one obtains a greater velocity for the flocculi and filaments of hydrogen than for those of calcium, which is probably due to their higher level. Indeed, if these filaments are merely prominences projected on the disc, their angular velocity will correspond to the level above the photosphere at which they occur. In the case of Royds' measurements, the observed velocity gives a height of about 30″ above the mean level of the photosphere.

Chromosphere. Prominences on the solar limb, their constitution, classification, and periodicity

During eclipses, when the photosphere is completely covered by the moon's disc, the chromosphere is visible to the naked eye as an atmosphere of a vivid red colour which surrounds the whole solar globe. Even in full sunlight it is always possible, with the spectroscope, to observe the chromosphere extending in different thicknesses all round the sun. For the better study

of its structure it is advisable to broaden the slit of the spectroscope slightly and to place it tangentially to the disc. In this position of the slit, or rather with the slit a few seconds of arc outside the disc, in the most intense lines (for example in $H\alpha$) the edge of the chromosphere is seen to be jagged and in

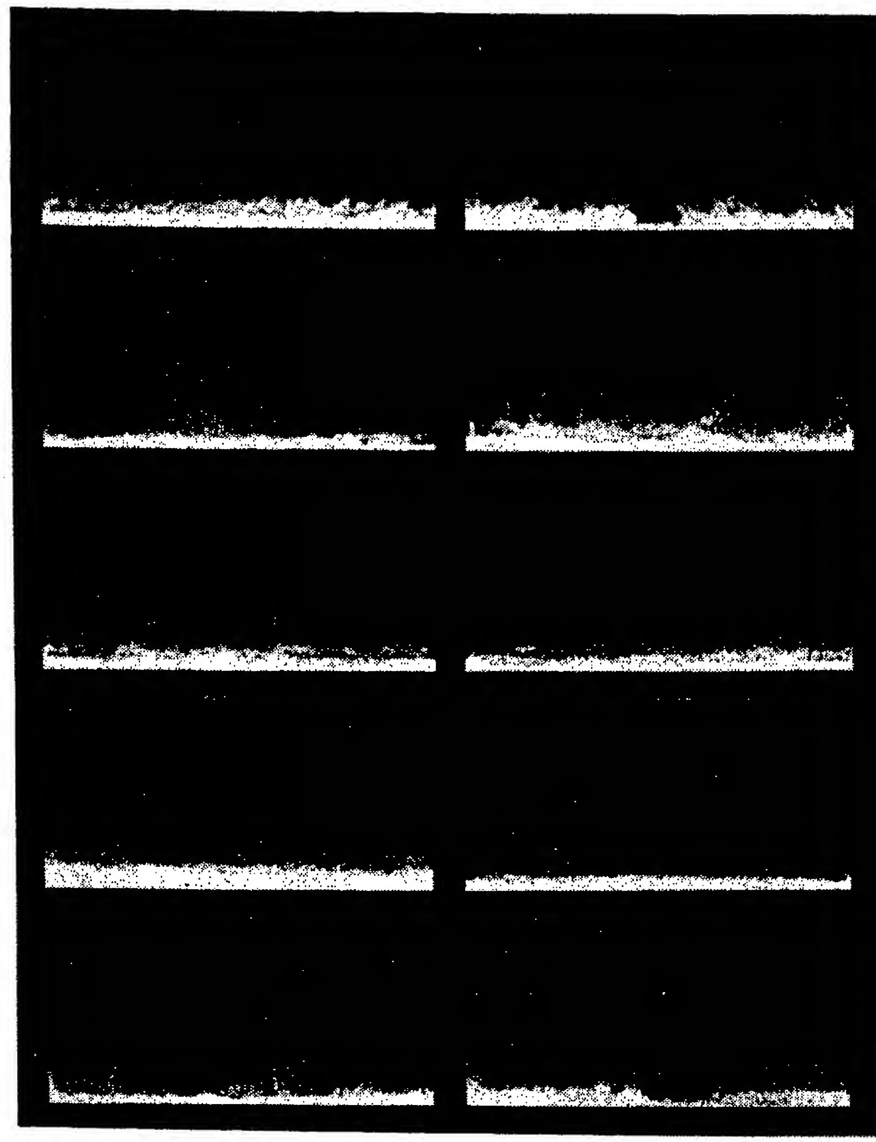

FIG. 66. Drawings of the chromosphere by P. Secchi.

continual agitation, this appearance being partly due to the terrestrial atmosphere and partly to actual chromospheric turbulence.

It is this chromosphere which Secchi describes as the *prateria infocata* (prairie in flames). At the base, i.e. in the part which is in immediate contact with the sun's surface, it has a more vivid hue than in its upper part, so that, when the slit of the spectroscope is placed perpendicularly to the limb, the more

intense lines are seen to end in luminous points in the form of a lance whose extension depends on the intensity of the lines, the power of the telescope and the atmospheric conditions. In the more intense lines the chromosphere may generally be said to have a height of 10″ to 15″ in full sunlight, but during eclipses a much greater height may be observed.

The fine points of which the chromosphere consists, which may well be compared to flames, may all be inclined in the same direction or in opposite directions. Sometimes the change of direction is very pronounced at the poles, where one may observe a series of direct vertical flames of varying heights, of the same type as those seen in the solar corona (page 247). In calm regions the chromosphere may appear over a vast tract of surface (sometimes over more than a quarter of the sun's circumference) with the points inclined in the same direction, after which they suddenly change their direction. In the neighbourhood of the equator and in general in the disturbed zones they even assume the aspect of flames with directions varying from one moment to another.

It appears that in the solar atmosphere there is no regular circulation which could manifest itself at the level of the chromosphere at a particular direction of the luminous points. According to Secchi, during the periods of maximum activity their inclination is more constant, more regular, and directed towards the poles. During the periods of calm there is less regularity, or at any rate the regularity is not so general.

Often, chiefly in the sunspot regions, the chromosphere presents the appearance of a very intricate lattice-work whose confused surface seems to be composed of brilliant clouds analogous to flocculi; some of these clouds spread or expand so as to form small elevations diffused at the edges. These elevations assume different aspects and dimensions until they become real "prominences," so that there is no sharp and precise demarcation between chromosphere and prominences; nevertheless, it has been agreed to describe the elevations by this name when their height exceeds the mean level of the photosphere by 30″.

The height of the chromosphere is not uniform around the solar globe. Respighi, measuring in the $H\alpha$ line a height of about 12″, noted as early as 1869, between a minimum and

maximum of solar activity, that the chromosphere appeared higher in the neighbourhood of the poles than at the equator. In 1875, near minimum period, Secchi noted the same circumstance and also the fact that in the polar regions, during periods of almost general calm of the sun, there always exists

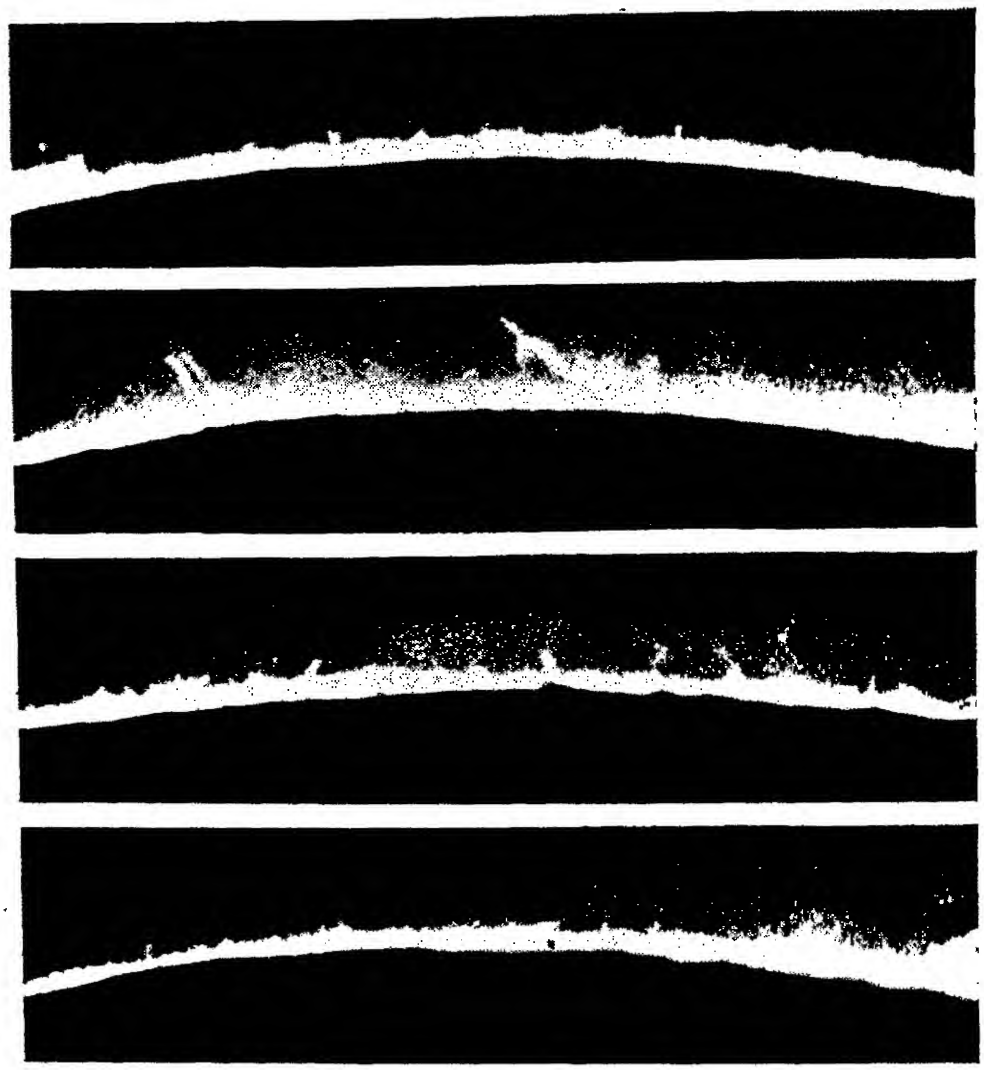

FIG. 67. Photographs of the chromosphere taken during total eclipses.

a very considerable activity which manifests itself by the considerable brightness and dimensions of the flames composing the chromosphere.

After these initial observations of Respighi and Secchi, it was of interest to take regular measurements of the height of the chromosphere and to follow its changes throughout the cycle. The measurements effected by placing the slit of the spectroscope perpendicular to the solar limb and determining with the micrometer the height of the inverted line $H\alpha$ from

the end point of the absorption line to the point at which the emission line terminates in the background of the heavens, cannot be very precise owing to the very mobility and form of the chromosphere. Nevertheless, if the sky is sufficiently transparent and the images well defined, measurements effected at several latitudes around the limb may tell us where the chromosphere is the more elevated and where it is less so.

Determinations of this type are, in conjunction with the international programme of solar observations, effected at

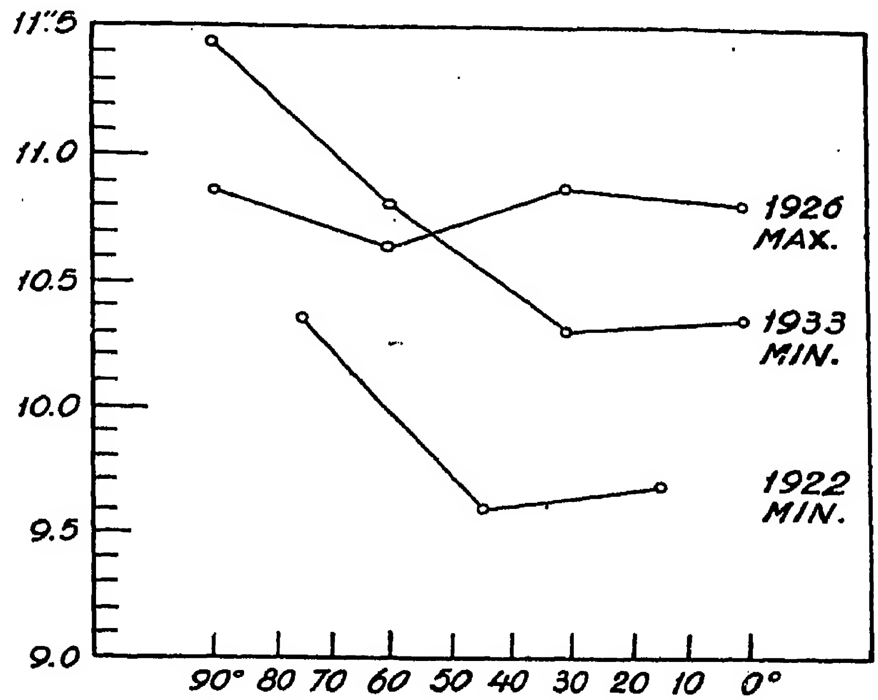

FIG. 68. Height of the chromosphere observed at Arcetri and referred to a quadrant of the sun's limb.

several observatories, of which may be mentioned Arcetri, Catania, Madrid, Prague and Taschkent.

At Arcetri, with Amici's equatorial of 36 cm aperture and 5·40 m focal length, in conjunction with a Zeiss spectroscope (Figs. 17 and 18) giving a dispersion of 15° from $H\beta$ to $H\alpha$, a series of measurements of the height of the chromosphere have been carried out since 1922, every 30° of latitude, starting from the north pole. During the minimum periods, about 1922 and 1933, a mean height of 10″ is found for line $H\alpha$; moreover, at the poles the chromosphere is about 1″ higher than at the equator. On the other hand, around a maximum period, as in 1926, the chromosphere was seen to

be somewhat higher (about 11″), but uniformly distributed around the sun's limb. Observations at Madrid also confirm this result.

Of course, observations of this kind extending over several cycles are necessary in order to establish these results with absolute certainty; in the meantime it is interesting to note how, according to the theoretical researches of Milne on the equilibrium of the chromosphere as established between the force of gravity and the pressure of radiation, the variations in height of the chromosphere are a probable consequence of the equilibrium itself, because the distribution of density is very sensible to the immediate changes which the reversing layer has undergone. A diminution in the intensity of solar radiation, too slight to be otherwise perceptible, might, according to Milne's calculations, be the cause of a very considerable temporary decrease in density over some thousands of kilometres on the photosphere.

Other methods may also be selected for determining the height of the chromosphere in various wavelengths, as for example that devised by Fox, which consists in causing two diametrically opposite points of the sun's disc to be reflected on the slit of the spectroscope by means of prisms whose distance can be altered by micrometer screws. The double height of the chromosphere for the line examined is given by the difference between the maximum and minimum distances of the prisms, for which the light coming from the two opposite limbs showed reversal of the lines. Observations effected with the 40-inch refractor of the Yerkes Observatory give for the $H\alpha$ line a mean height greater than 10″, and for the D_3 line of helium a height greater than 8″.

D'Azambuja at Meudon has made use of the spectroscope for comparing the diameters of the images formed successively in the wavelength of an emission line and in that of the neighbouring continuous spectrum. Pettit employs the spectrohelioscope and finds for $H\alpha$ a height of about 8″. Results naturally differ for telescopes of different powers, with spectroscopes of different dispersive power and used in places with different conditions of atmospheric transparency.

All heights determined by these methods are considerably lower than those measured in the reversing layer and in the

chromosphere during solar eclipses, which is due to the large quantity of diffused light in full sunlight. During these eclipses there are thus more trustworthy values for the absolute height. But the observations carried out continuously in full sunlight are important for establishing the possible variations at the different latitudes and in the course of the cycle, as stated above.

The flames or prominences, which appear more or less brilliant, extending to various heights above the sun's disc, are visible to the naked eye during total eclipses, but in full sunlight they have only been seen since 1868, when they were first looked for with a spectroscope attached to the telescope.

As early as 1866 Sir Norman Lockyer was of the opinion that prominences consisting of incandescent gases could be observed with the spectroscope, but it was not until October 1868 that he had a suitable instrument at his disposal and could observe them in full sunlight. However, only a few months before, viz. on August 18, during a total eclipse of the sun that was visible in British India, Janssen, who was there to observe it, noted with the spectroscope the great brightness of the prominences, which gave intense emission lines. Immediately after the eclipse he established the fact that, by the methods we are about to describe, prominences could be seen in full sunlight. Both Janssen and Lockyer reported their discovery independently and simultaneously to the Academy of France, and from that date observations of prominences at the solar limb have been continued regularly.

If the slit of a spectroscope attached to the telescope is directed to a point of the solar limb at which there may be a prominence, its spectrum is seen to be composed of more or less intense and more or less numerous emission lines, according to the intensity and quality of the prominence itself. If the slit is shifted in such a manner as to remove it gradually from the limb, the lines will continue to appear more or less long according to the extent or shape of the prominence, and up to a distance from the limb corresponding to its height.

For better observation of the complex form of prominences it is expedient, as was first suspected by Huggins in 1869, to open the slit of the spectroscope in such a manner that instead of the lines we see so many monochromatic images of the prominences itself. Naturally, by broadening the slit we reduce

the sharpness, but in general the prominences are so intense that for proper broadening of the slit (which depends on the dispersion of the spectroscope) the complex forms of the prominences are clearly seen, either totally or partially, according as, in view of their height, they can or cannot be wholly contained in the aperture given to the slit.

Father Secchi and Respighi at Rome were among the first

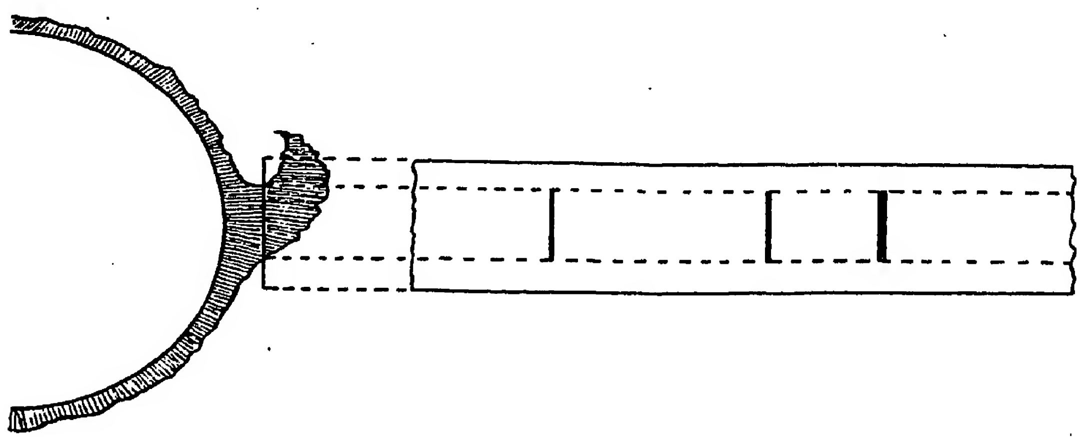

FIG. 69. Observation of prominences with the slit of the spectroscope at a tangent to the solar limb.

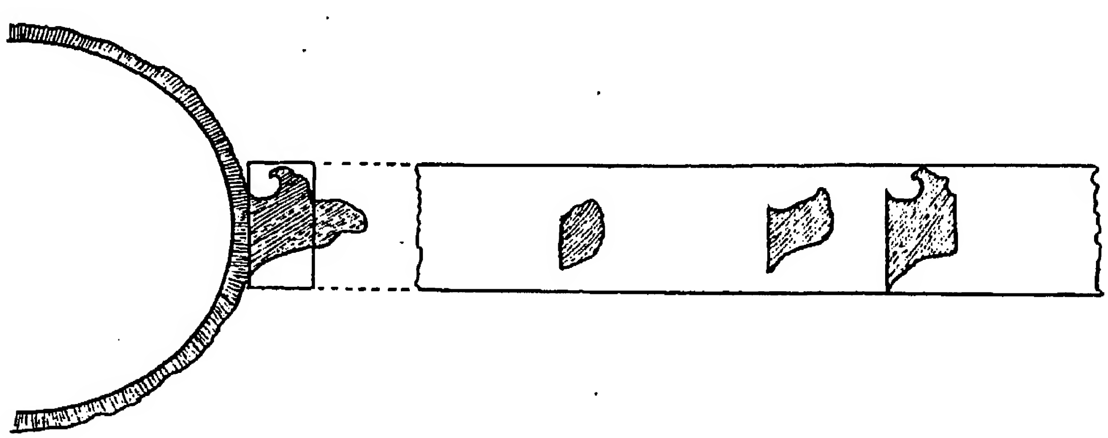

FIG. 70. Observations of prominences at the solar limb, with broadened slit.

to observe prominences in a regular manner, and the former observer established the fact that, unlike spots, prominences may be scattered all over the solar latitude, from equator to pole, and that they are very numerous; in the year 1871 alone he counted as many as 2,767.

Prominences may assume the most varied forms, such as clouds, plumes of smoke or vapour; they may look like trees, feathers or fountains, as can be seen from the very fine

drawings by Secchi or in modern photographs. These forms may be maintained for some time or may vary rapidly. According to their variability Secchi divided them into two categories: "quiescent" and "eruptive."

The spectrum of prominences consists, as stated, of emission

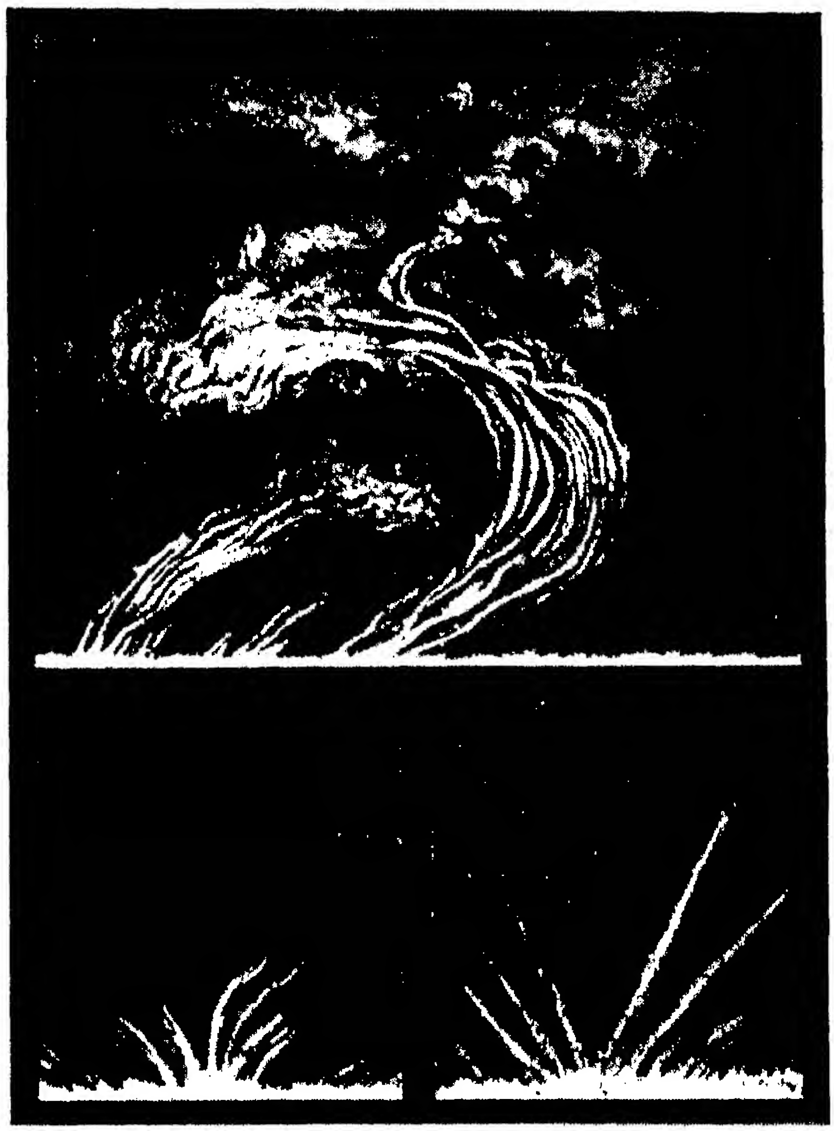

FIG. 71. Drawings of prominences by Father Secchi.

lines belonging to the Balmer Series of hydrogen, to ionized calcium (the lines H and K), and to helium (line D_3). These are the principal lines which are always seen, but many other belonging to neutral or ionized metals are seen during total eclipses or even in full sunlight in the more active and intense prominences, in which class the eruptive ones fall. In these are lines of *Fe*, *Mg*, *Ti*, *Sr*, etc.: it may be stated in general that the spectrum of prominences contains the brightest lines

of the flash spectrum, and that the lines vary in intensity according to the conditions of temperature and pressure of the prominence concerned.

The occasional appearance of the continuous spectrum is an indication of abnormal pressure. With sufficiently long exposures and under good conditions of atmosphere transparency, the spectrum of prominences would probably appear identical with that of the flash, except for some lines like those of helium which are found to be very intense in prominences, whilst those due to elements like barium are weaker. This behaviour suggests that the forces supporting the prominences from the chromosphere act in such a way as to separate out the heavier elements, one of which is barium.

The following classification of prominences, which is more detailed than that of Secchi, has recently been proposed by Pettit:

(1) "Active" prominences, which seem to be subject to the influence of an area of attraction or of a nearby spot.
(2) "Eruptive" prominences, which come out rapidly in a more or less vertical direction.
(3) Prominences of spots in the form of closed rings or jets, like the spraying of a fountain.
(4) "Vortex" prominences, in the form of spirals or tightly twisted ropes.
(5) "Quiescent" prominences, which alter their form more slowly than all the foregoing ones.

In reality all prominences are active, but the degree of activity varies. Classes (1) and (2) are intimately connected, so that one and the same prominence may present the two phases at the same time or pass from one to the other. Although a spot may or may not appear in conjunction with prominences of these two classes, both may be associated with class (3).

We generally speak of prominences above the chromosphere when they extend beyond 30″ above its level, and hence, while 30″ is the minimum height, prominences are often noted as high as 2′ or 3′ and in exceptional cases even as high as 9′ or 10′, viz. about 35 times the earth's diameter. Also the base of prominences may be very limited, measuring only

some tenths of a degree of the solar limb, and may extend over several degrees, in exceptional cases up to 20° or 30°, viz. 20 to 30 times the earth's diameter or even more.

Of course prominences do not extend only in the two dimensions in which they are seen on the solar limb, but in three, and the third dimension can be determined by com-

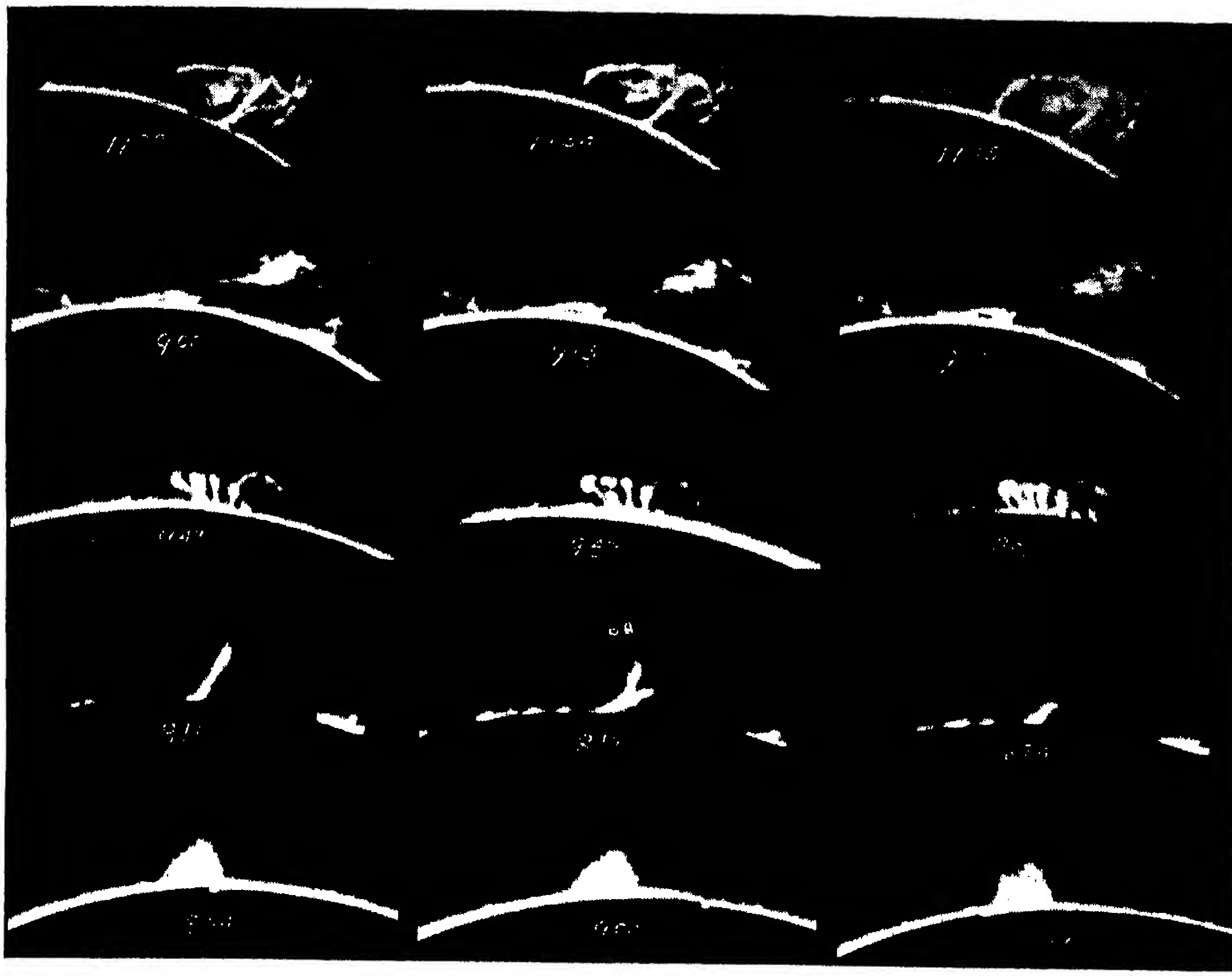

FIG. 72. Three exposures of each of Pettit's five types of prominences.

paring their shape when they are projected on the solar disc with the shape they assume at the limb. As already stated (page 115) prominences projected on the disc occur as flocculi, generally dark, which are then called filaments or, in the case of prominences of considerable activity, as bright flocculi. The filaments are often curved, and when they are radial or near the centre of the disc we can measure their real thickness.

Measurements effected by Pettit show that this thickness

is exceedingly small, varying in a large number of determinations from 6000 to 12,000 km. The length is very variable; few prominences are shorter than 60,000 km, but a length of 600,000 km is exceptional, although cases have been noted in which a line (though not a continuous one) of prominences extended over more than a quarter of the sun's circumference. In the synoptic charts of the Meudon Observatory, which for each solar rotation give the flocculi and filaments projected on the disc, there are several examples of this type.

The height is very variable, especially in the first four classes, the greatest height observed up to now being 1,000,000 km in an eruptive prominence photographed at the McMath-Hulbert Observatory on September 17, 1937.

We may thus consider the three-dimensional form of a prominence as a thin tongue of flame. This tongue of flame, which consists of incandescent gases, extends some thousands of kilometres into the chromosphere and is joined to the latter by columns of gas as a tree is joined to its roots. The following dimensions may be considered as representative of prominences: thickness 10,000 km, length 200,000 km, height 50,000 km, giving a volume about ninety times that of the earth. One of the largest prominences is that observed on May 29, 1919, belonging to the class of eruptive prominences in the form of a large vortex connecting two points of the solar limb and possibly continuing into the sun's interior. It appeared on March 22nd, at the eastern limb, in latitude $-35°$, increasing gradually in intensity and height at each successive appearance. On May 28th the prominence appeared as an enormous mass of twisted streamers attaining a height of $2 \cdot 7'$, as if protruding from two columns at $-37°$ and $-41°$, the principal mass of the prominence being situated parallel to the limb. Spectroheliograms taken by Pettit with the Rumford spectroheliograph, using the line H_3 of *Ca*II, show the prominences as a large arc extending between $-42°$ and $+6°$; it is to be noted that at $+7°$ there is a spot at the limb. At 2 h. 57 m. G.M.T. the large arc was completely twisted and probably in vortex motion, and began to free itself from the base; Fig. 74 shows it moving away and rapidly disintegrating. The vortex structure was also seen later, when the arc was breaking, removed increasingly far away from the

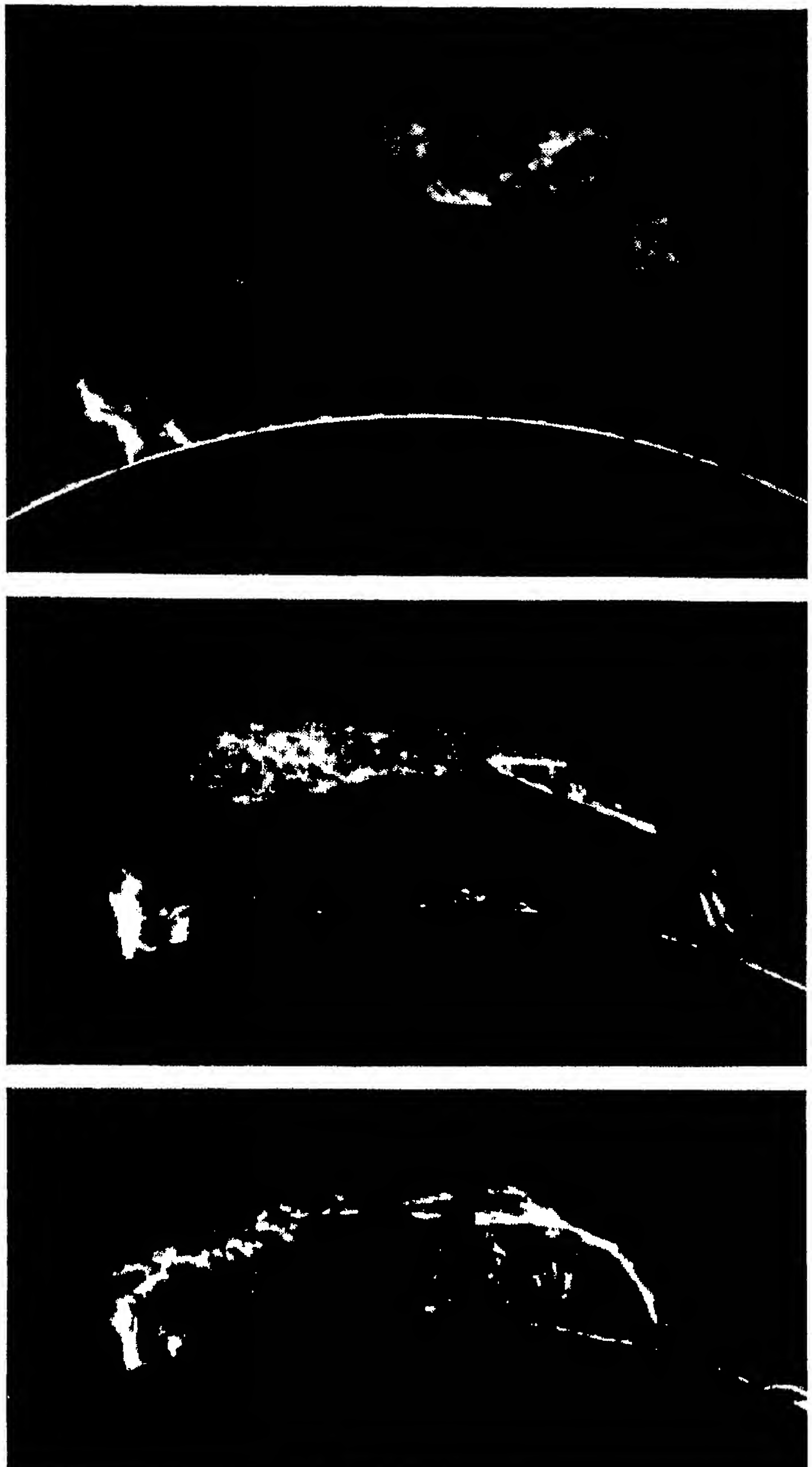

FIG. 73. Eruptive prominence of May 1919; line H_2 of calcium (Pettit). *From bottom to top*, 1 h. 41 m., 2 h. 57 m., 5 h. 33 m. G.M.T.

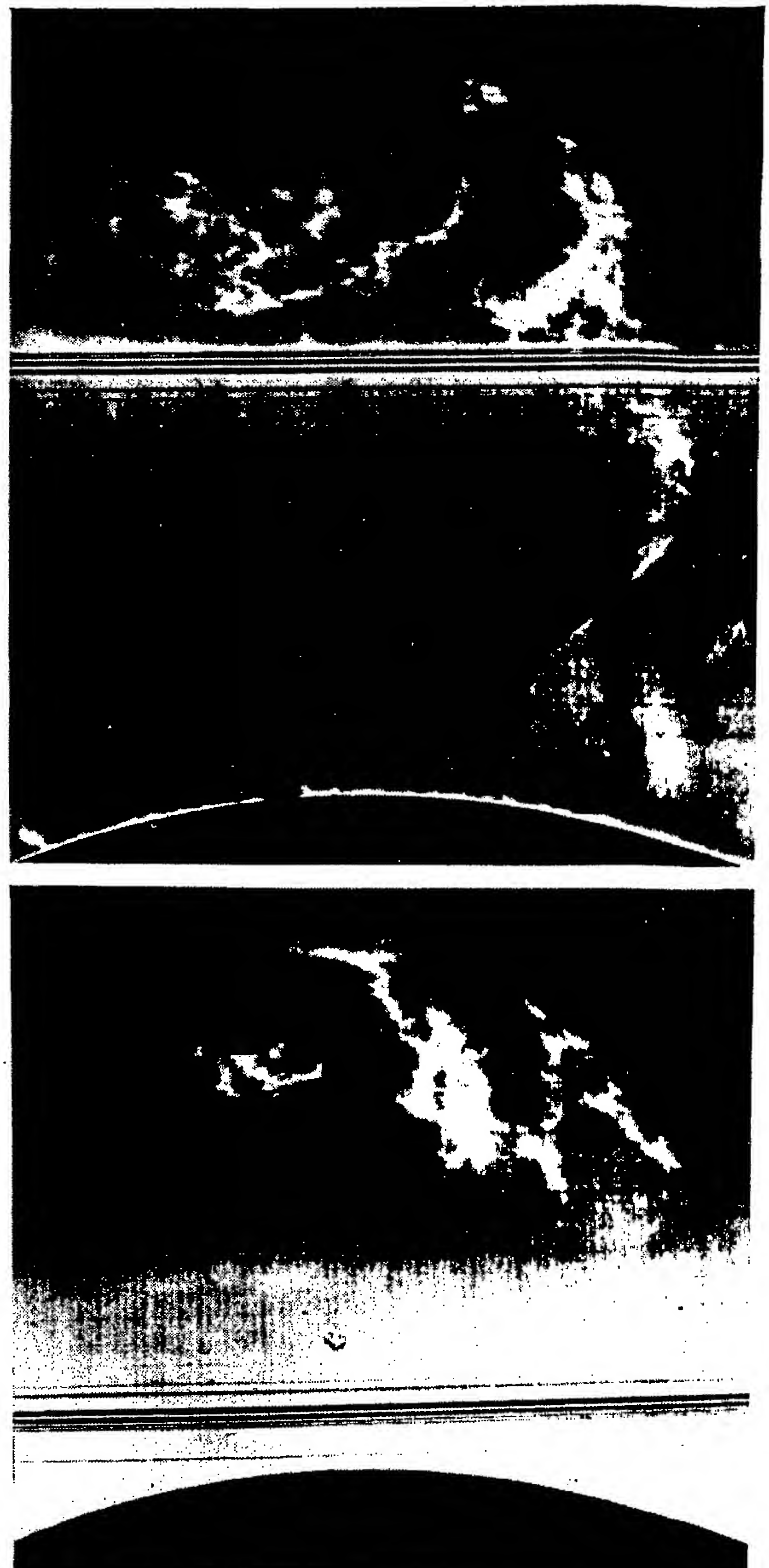

FIG. 74. Eruptive prominence of May 29, 1919; line H_2 of calcium (Pettit). *From bottom to top*, 7 h. 20 m., 7 h. 57 m. G.M.T. The black lines are due to discontinuities in the motion of the spectroheliograph.

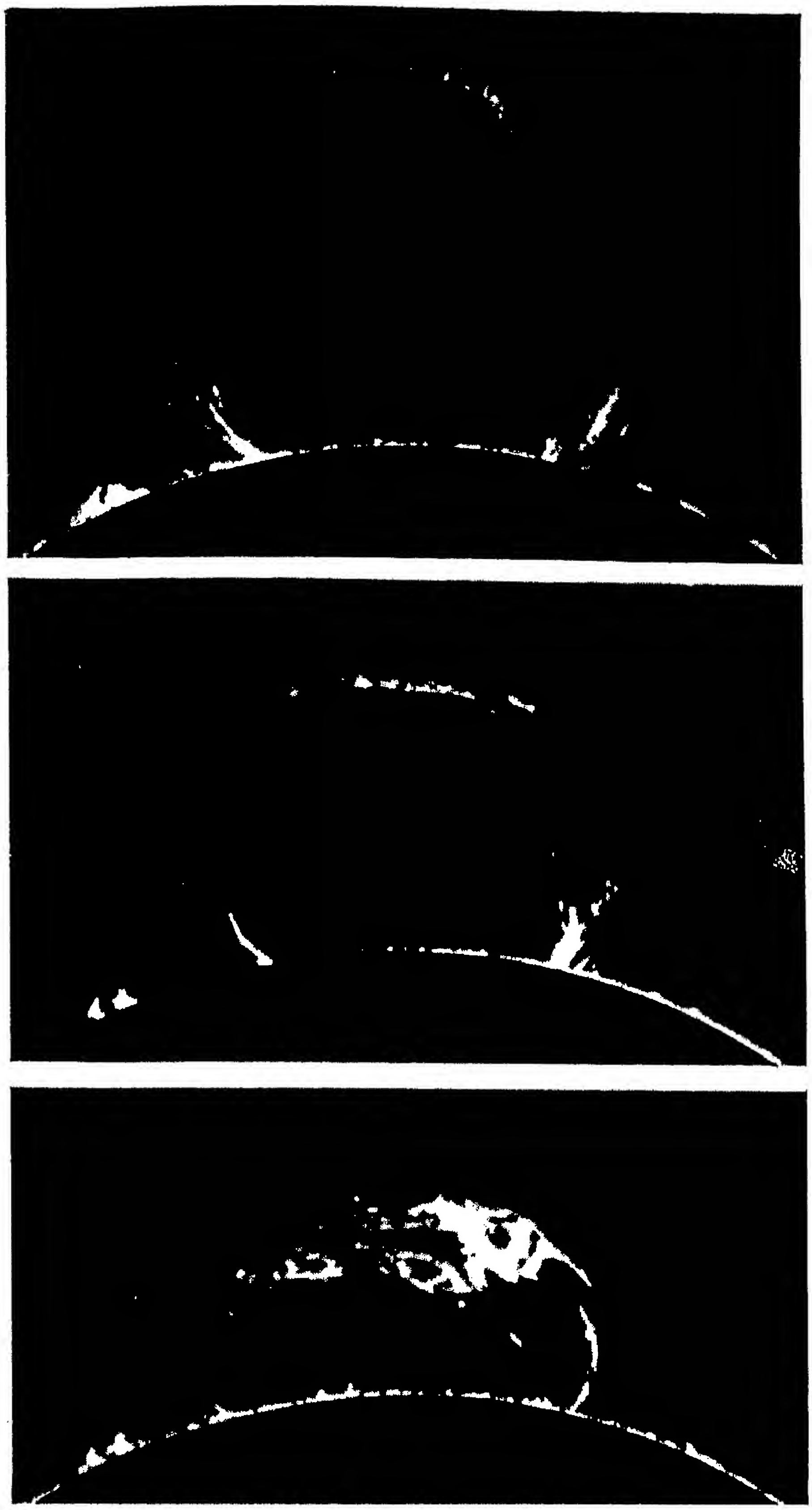

FIG. 75. Eruptive prominences of July 15, 1919 (Pettit).
From bottom to top, 3 h. 8 m., 3 h. 52 m., 4 h. 7 m. G.M.T.

sun until it reached the maximum height of 17′ (at 7 h. 57 m.), almost equal to 800,000 km (Fig. 74).

Similar in form to this prominence, but of a more rapid development, is the other of 1919 (July 15th) which was also photographed by Pettit. It appeared for the first time on July 1st in the form of two streamers at $-11°$ and $+18°$ latitude, while there was a spot at $-14°$. On July 15th, in the first photograph taken at 3 h. 8 m. (Fig. 75), the prominence with the connection between the two eruptive centres had already completely developed to a height of 6′, and successive exposures showed it in rapid vertical motion. The maximum height attained was 16′, and the time of ascension from the first exposure was only 1 h. 26 m.

Centres of attraction and repulsion certainly act on the material of prominences, as may be seen in the neighbourhood of spots; moreover, the extremities of prominences often present the appearance of being urged in a given direction by horizontal currents, which may give the impression of an actual circulation of the solar atmosphere. Secchi entertained this idea and effected some observations concerning it in 1872 (page 133). Recent researches by Slocum would seem to indicate that at a certain height (about 30,000 km) above the level of the photosphere there are currents tending to draw the prominences towards the poles in medium latitudes (between 20° and 55°) and towards the equator in high latitudes (about 65°), while at the equator neutral conditions prevail.

In this connection Evershed notes that it is difficult to imagine that at the height attained by prominences the solar atmosphere has a sufficient density to produce currents of this kind, and on the other hand prominences are often seen which open out in both directions like a tree at high elevations; or neighbouring prominences which incline in opposite directions, on which account it is not probable that these shapes are due to solar winds. The fine filaments which very often protrude from prominences and which, according to the hypothesis of currents, would be due to systematic currents, are on the other hand noted at the two sides of a prominence, and often unite or almost unite the tops of neighbouring prominences. So one is led to imagine a reciprocal action, which may be

that of a vortex produced at the interior and continuing at the exterior of the sun's surface.

It has been noted by various observers how, in eruptive prominences, the ascending velocity of the materials comprising them increases with the height they attain, and hence in general with the time. In order to study the nature of the forces acting, Pettit carried out an examination of observations made with the spectroheliograph for a given prominence in various phases of its development. Typical are, for example, those of 1919 (May 29th and July 15th) reproduced here (Figs. 73 and 75). In these two prominences the motion is seen to be uniform for a certain interval of time, after which it suddenly increases, but remains uniform at a greater velocity, as if at that moment an impulse had been imparted to it.

In the prominences studied the maximum mean velocity is 153 km/sec., with a maximum velocity, in three cases, of 400 km/sec. In no case is the motion of these prominences found to be in accordance with what it would be under the same conditions for a body projected upwards and subject to the gravitational force of the sun. Thus, in the case of the prominence of May 29th, the initial velocity was 5·5 km/sec.; if, in obedience to gravitation, it should have risen up to 83 km with decreasing velocity, it would subsequently have fallen back on the sun's surface, but instead, it continued to ascend at uniform velocity to a height of 50,000 km; there a second impulse increased the velocity to 9 km/sec up to a height of 119,000 km, a third one increased it to 13 km/sec up to a height of 191,000 km, and a final impulse to 32 km/sec up to a height of 230,000 km, when the prominence after eight hours had reached its maximum height of about 600,000 km.

The conditions governing these phenomena have been studied theoretically in various ways. Milne propounds the hypothesis that the chromosphere is held in suspension by selective radiation pressure, and finds that in several of the cases studied by Pettit a parabolic curve may represent the trend observed, without having to introduce impulsive discontinuous motion. But even so, in his hypothesis, sudden changes of velocity followed by periods of uniform motion are perfectly compatible with motion under the action of radiation pressure; we need only assume that the photosphere becomes

brighter for a brief period and then reverts to its original luminosity.

The question of the force acting on prominences has been dealt with also by Bobrovnikoff, using the same methods as he employed for calculating the repulsive force acting on comets. In thirteen cases of calcium prominences, and in eight hydrogen prominences, he finds that the repulsive force is always greater in the case of hydrogen, and that it increases with the mean distance of the prominence from the solar surface. This may be interpreted as due to increased velocity and the resulting Doppler effect, in accordance with Milne's theory. The investigation reveals a remarkable analogy between prominences and comets. The motions of CO^+ in a comet's tail are also influenced by the sun's repulsive force, and the sudden changes of velocity and of repulsive force frequently observed in comets have all the characteristics of actual explosions. Pettit successively proved that the observed velocities of prominences are well confirmed by a law which states that when the velocity of an eruptive prominence alters, the new velocity is a small multiple of that immediately preceding it.

Pike, basing himself on Milne's theory, discussed the effect of the bright areas near the prominences in equilibrium with radiation pressure, and found that the facular areas, of the order of 200,000 square kilometres, radiating in the region of the H and K lines may, at an actual temperature of 7500° absolute, cause the average velocity observed in the eruptive prominences.

McCrea discusses the physical theory of radiation pressure on the excited hydrogen atoms in the chromosphere and finds that radiation pressure can only amount to one-tenth of the sun's attractive forces; he has therefore to introduce the conception of "turbulence" in order to explain the residual upward force.

In all these theoretical considerations an accelerated continuous motion is formulated which is in contradiction to the principle of uniform motion found in Pettit's researches. This observer is of opinion that the difficulty of explaining how prominences can have a uniform ascending motion may be due to the fact that the presence of the corona through which the material of the prominence moves is not taken into account.

However that may be, it is a fact that observations are still being carried out with the spectroheliograph in order to establish in a more definite manner the characteristics of the motions of prominences.

With regard to the mass of prominences, Pannekock and Doorn find that an ordinary prominence has a hydrogen content of 2×10^{13} atoms per cubic centimetre. The calcium

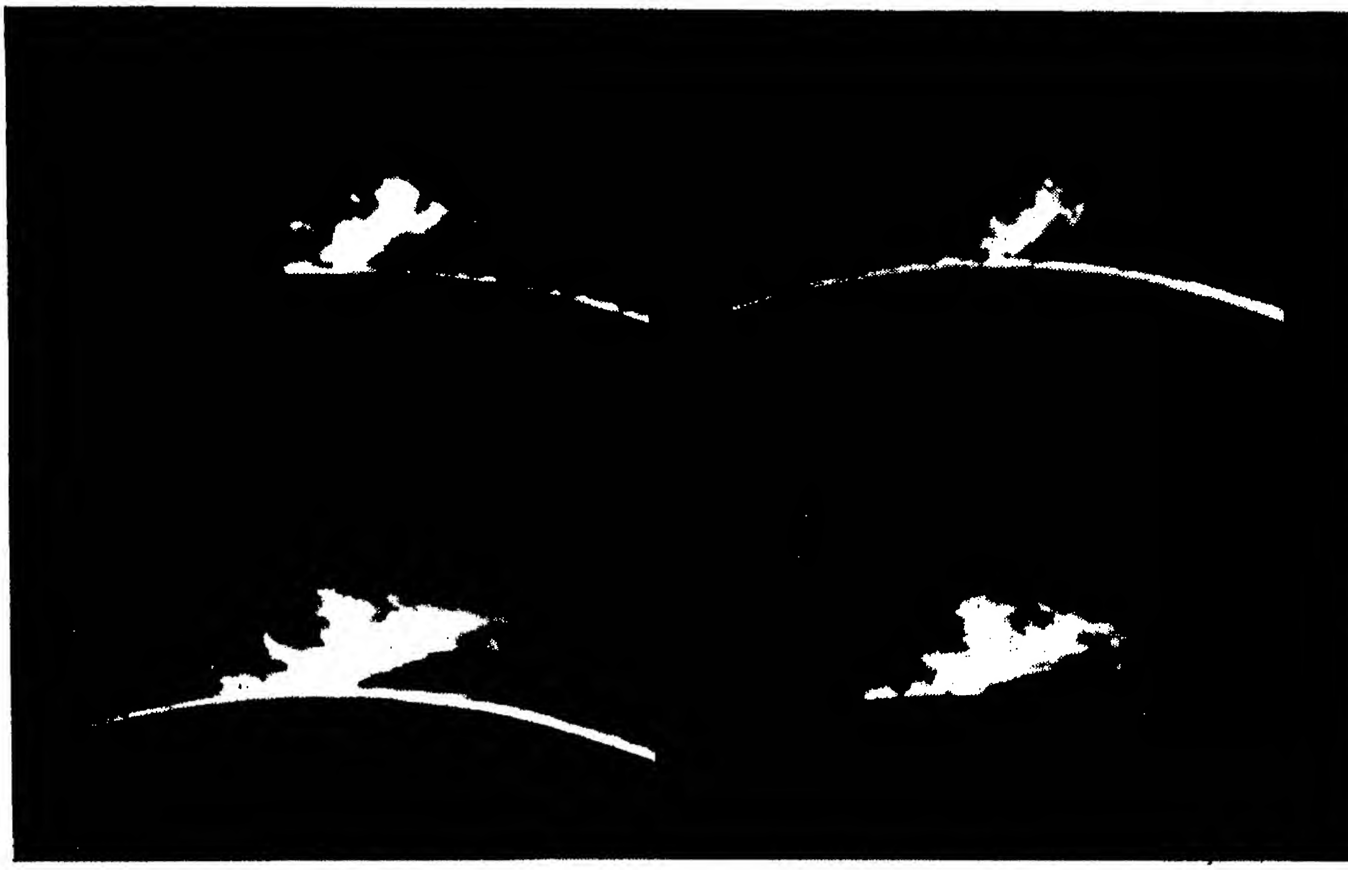

FIG. 76. Comparison between spectroheliograms obtained with the $H\alpha$ line (above) and with the K line (below) on March 10, 1926 (Mount Wilson).

content is negligible. On this basis a typical prominence of 10,000 km thick, 200,000 km long, and 50,000 km high, would have the mass of a cube of water with a side of 15 km. According to this hypothesis the mass of the prominence of 1919 (May 29th), which ranks amongst the largest hitherto observed, is four times greater than that of the typical prominence.

The best method of determining the distribution of the various elements in prominences consists in photographing their spectrum during total eclipses, and this, as we shall see (page 238), has been done during the brief moments of totality which have been hitherto available.

Continual and systematic researches have also been commenced with the spectroheliograph, the prominences observed particularly in the *Hα* line being compared with those observed with the lines H and K of ionized calcium, for which an extensive series of observations is available. Comparison

FIG. 77. Quiescent prominence 175,000 km high, photographed at the Mount Wilson Observatory in hydrogen light (*Hα*) on July 10, 1917 (the white disc represents the size of the earth).

between these photographs taken at the Mount Wilson and Yerkes Observatories and the visual ones of Catania, led to the conclusion that calcium prominences attain a greater height than hydrogen ones. Also the curve of the areas in the period under consideration (1906–1908) is generally lower for hydrogen than for calcium. It was also found that the calcium prominences have a distribution that is somewhat different from that of hydrogen prominences.

Simultaneous or nearly simultaneous photographs with the same instrument or with different instruments, of prominences in these monochromatic radiations, show that as a rule the prominences in calcium light are more extensive than those of hydrogen, and that the former are accompanied by numerous filaments, which in the latter are less intense or entirely absent (Fig. 76). This may of course be an effect of photographic contrast or of luminosity of the instrument in the two radiations, the more so as, apart from the extent and the difference in the filaments, the two images are absolutely alike; hence we are impelled to the conclusion that the two elements are at any rate mixed.

Perepelkin at the Poulkovo Observatory finds that the

FIG. 78. Eruptive prominence photographed during the eclipse of June 8, 1918 (Yerkes Observatory).

velocities of prominences for *Ca*II are generally greater than those for hydrogen, and that there is a correlation between the two velocities which seems to be in accordance with the theory that the velocity of prominences is due to radiation pressure.

Subsequent researches and comparisons of this type are necessary for the better establishing of any reported differences and also of the behaviour of any electric fields of force whose action is evidenced by the coronal rays which often accompany them.

With international co-operation a statistical study is being made both of prominences at the limb, and of sunspots, faculae and flocculi, with a view to establishing their area, shape, distribution during the various cycles, by visual and photographic observations. The visual observations were commenced in 1869, immediately after the Janssen–Lockyer

discovery, by Respighi at the Osservatorio del Campidoglio, and were continued by Father Secchi, Tacchini, and many others.

The appearance of the whole solar limb, viz. its spectroscopic image in the light of the $H\alpha$ line, is given from day to day in the *Memorie della Società degli Spettroscopisti Italiani* from 1869 to 1911, in tables from which we can deduce the position angle and hence the latitude of prominences and the area

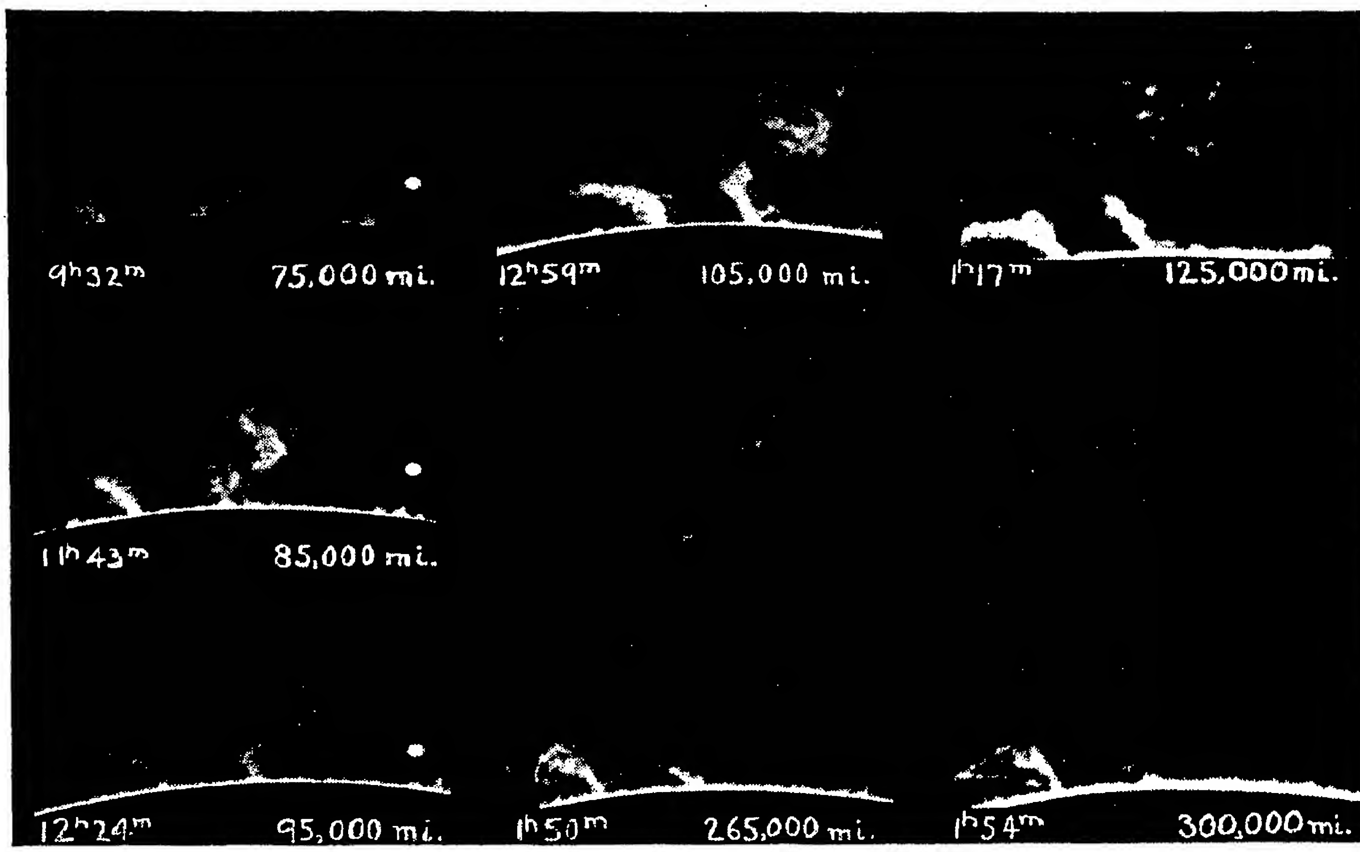

FIG. 79. Eruptive prominences with rapid ascending motion, October 8, 1920 (Yerkes Observatory).

they occupy. The publication of these spectroscopic images has been continued since 1922, under the auspices of the International Astronomical Union, by the Arcetri Observatory, which is the collecting centre for all visual spectroscopic observations made in the various observatories. This material serves for the annual compilation of statistics of the distribution and area of prominences, for which a conventional unit of profile area called the "prominence unit" has been adopted. This unit is the area covered by an arc of one degree of the solar limb in length, and one second of arc of the celestial sphere in height.

The trend of prominences and their relation to the cycle of solar activity has been studied by Riccò, Lockyer, and several other investigators. Following in the wake of these observers, and making use of spectroscopic images of the solar limb

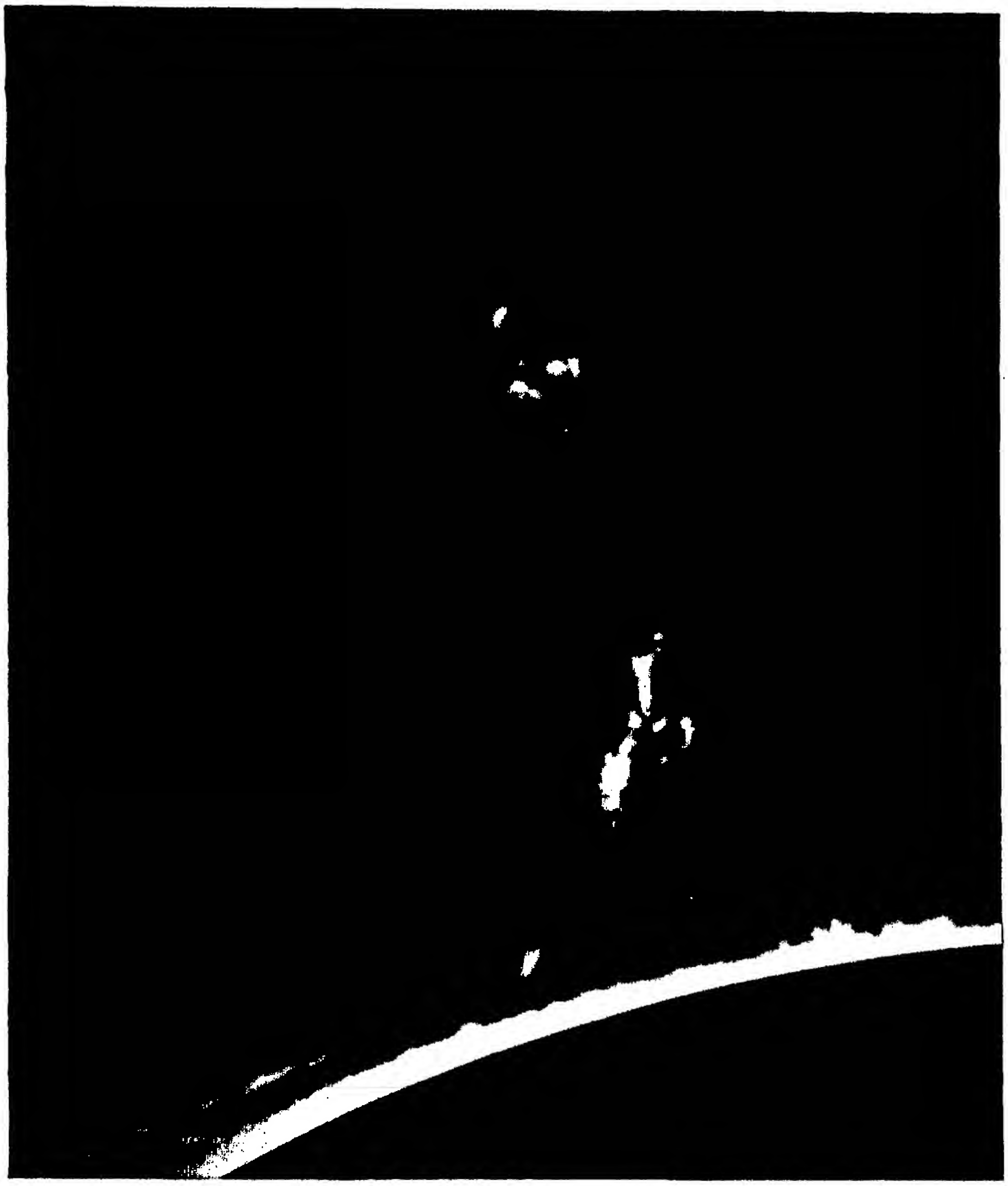

FIG. 80. Eruptive prominence, August 6, 1931, 17 h. 35 m. G.M.T. (Pettit).

from 1880 to 1931, G. Bocchino calculated the average diurnal areas of the hydrogen prominences for every 5° of latitude. The results of this research may be collected in the two graphs (Figs. 82 and 83).

From the trend of the various lines in Fig. 82 (abscissae:

years; ordinates: degrees of latitude) we may conclude that on the sun there are two zones in each hemisphere in which prominences are most frequent: one at high latitude and one at a relatively low latitude; these zones

FIG. 81. Eruptive prominence, August 6, 1931, 18 h. 16 m. G.M.T. Height above the photosphere, 450,000 km (Pettit).

follow two different and well-defined laws. As a matter of fact the high-latitude zones appear in both hemispheres one or two years after the maximum sunspot period, at a latitude of about $\pm 45°$, where they remain stationary or almost stationary, until the minimum period when they shift rapidly

towards the poles, reaching them at the maximum period and disappearing almost immediately. The low-latitude zones, on the other hand, commence at ± 30° about one year after the minimum sunspot period and gradually move towards the equator; they are thus at a latitude of ± 25° in the maximum period and at a latitude of ± 17° in the minimum period. It is evident that the high-latitude zone is in no way associated with the sunspot zone; but in the case of the low-latitude zone it is interesting to compare its trend with that of the sunspot zone. For this reason we have given in the diagram the lines representing the well-known shift in latitude of sunspots year by year in the two hemispheres. In this way it may be seen that prominences show, with respect to spots, a phase-shift of about one year; in other words, the phenomenon of prominences, a disturbance in the high solar atmosphere, occurs with a time-lag of one year as compared with the occurrence of sunspots at their highest latitude, and continues constantly throughout the cycle at a more northerly or more southerly latitude of 10°.

Finally, at the period of maximum activity, whereas the sun only shows one single zone of spots, viz. at ± 15° in each hemisphere, there are on the other hand two zones of prominences: one at ± 25° and hence at 10° more southerly or more northerly than the sunspot zones, and one in the vicinity of the poles. At the minimum period, while there are two sunspot zones for each hemisphere: one at ± 20° belonging to the new cycle and one at ± 7° belonging to the cycle that is about to end, prominences are distributed over three zones: two low-latitude zones, viz. a zone at ± 30° belonging to the new cycle and a zone at ± 17° belonging to the old cycle, and a third zone at ± 45°.

In the second graph (Fig. 83) the activity of spots is compared with that of prominences by tracing the frequency curves of the two phenomena and expressing the first with Wolf's relative numbers (ordinates) and the second by means of the average diurnal areas expressed in prominence units (ordinates). For prominences the high- and low-latitude zones have been taken separately because their trend is different according to the progress of the cycle. By separately recording the average diurnal areas from 0° to ± 39° and from ± 40°

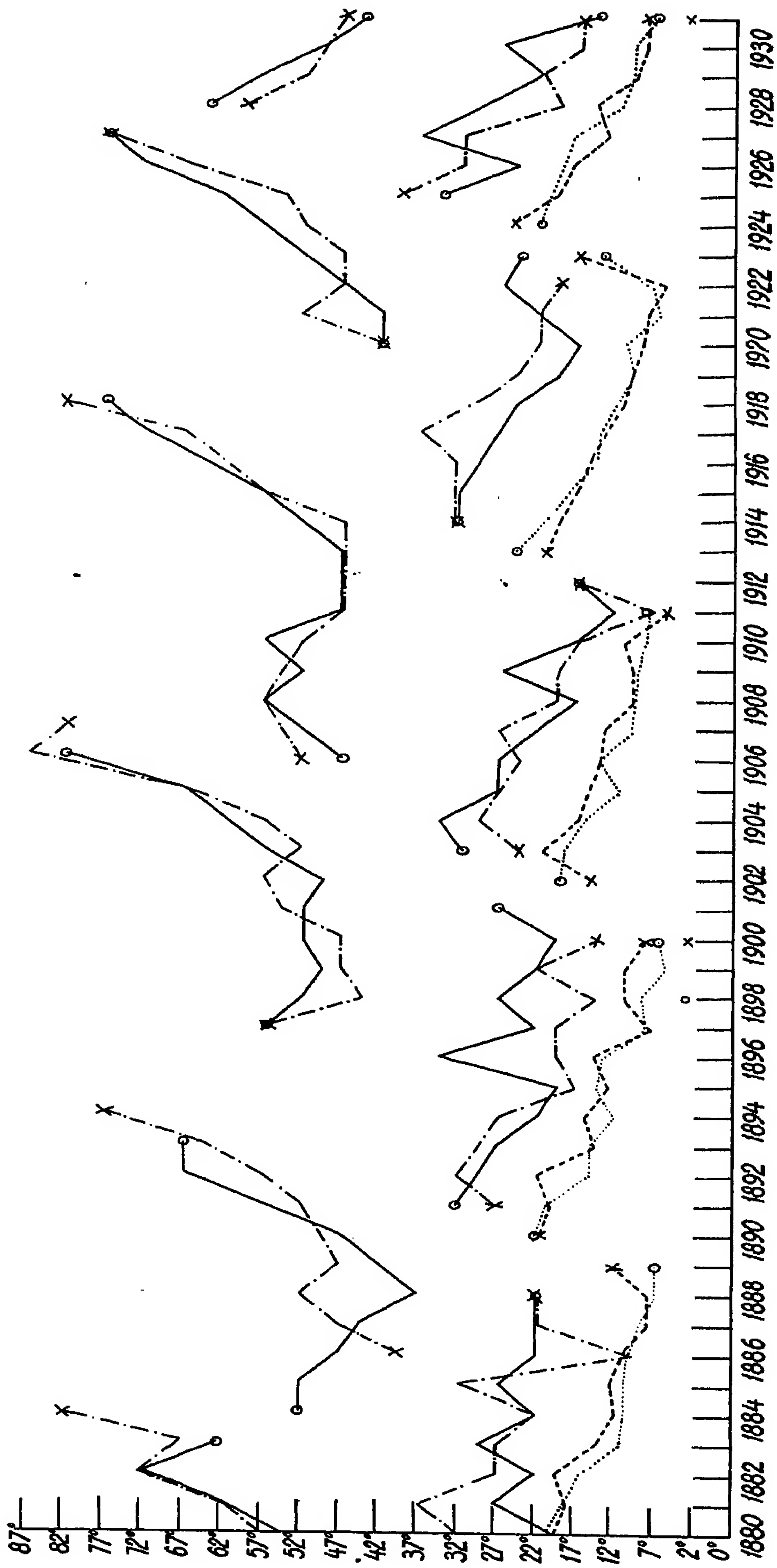

Fig. 82. Migration of prominences during the eleven-year cycle from 1880 to 1931.

Prominences { —— Northern hemisphere. -·-·- Southern hemisphere.

Spots { ······ Northern hemisphere. - - - - Southern hemisphere.

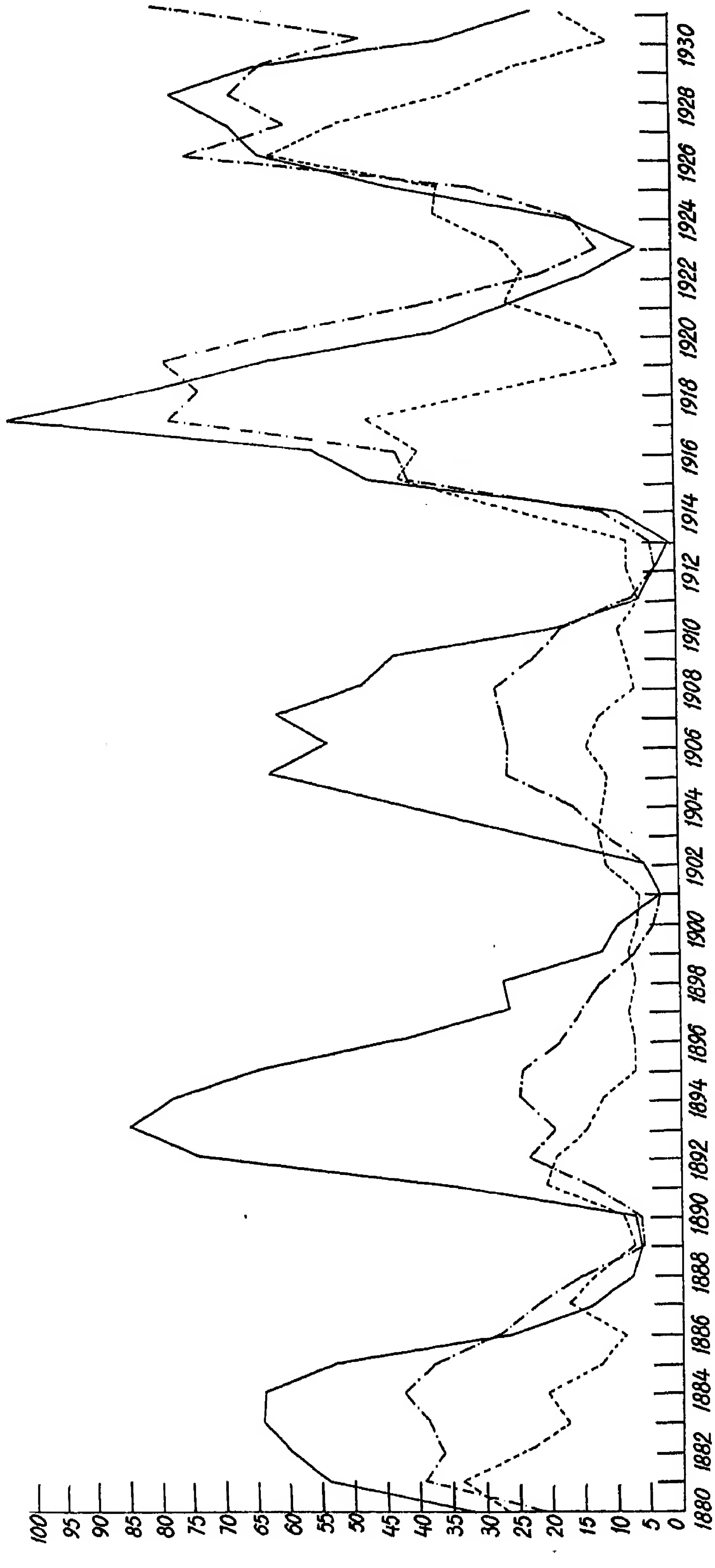

FIG. 83. Frequency of sunspots and prominences from 1880 to 1931.

——— Frequency of sunspots expressed in Wolf's numbers.

-·-·-·- Frequency of prominences in the low-latitude zones.

- - - - - Frequency of prominences in the high-latitude zones.

(in prominence units $\times$ 10^{-1}).

to $+90°$ we see in Fig. 82 that, in the low-latitude zone, prominences follow the trend of sunspots in intensity as well as in latitude. In the high-latitude zone, on the other hand, prominences begin to appear, as stated, at $\pm 45°$ about one year after the maximum, and continue until, about three years after the minimum, they reach their greatest activity at $\pm 60°$ latitude, to diminish again more rapidly and finally to disappear at about the maximum.

Spectroscopic Determination of the Period of Solar Rotation

The motions of the vapours present in the sun's atmosphere, when they take place along the line of sight, manifest themselves in the spectrum by virtue of the Doppler effect. These movements have an irregular or regular character. The irregular movements are generally observed in the disturbed regions of the sun, as for instance around sunspots, in eruptions, prominences, etc.; the regular movements are due to the sun's rotation about its axis, they are a maximum at the limb corresponding to the equator and are zero at the poles.

Distortions and shifts of the spectral lines, especially those of hydrogen, from their normal position in the spectrum, were observed by the early investigators such as Secchi, Young, Lockyer, particularly in prominences. In his book on the sun Secchi gives interesting drawings of the $H\alpha$ line observed with the slit of the spectroscope perpendicular to the limb, in very disturbed zones of the chromosphere.

An interesting use of the spectrohelioscope, applied to the observation of these radial movements by Hale, consists in placing in front of the second slit of the spectrohelioscope a small glass plate with plane parallel faces which can revolve about a vertical axle, so that when the small glass plate is turned to a certain angle the line and the surrounding region of the spectrum is seen to shift in the field of the object-glass of the spectrohelioscope. As is well known, a radial velocity shifts the $H\alpha$ line towards the violet when the hydrogen mass is approaching, and towards the red when it is receding. So a flocculus moving rapidly along the line of sight may remain absolutely invisible through the second slit, because the hydrogen line at that disturbed point is completely displaced

from its normal position. If the small glass plate is then turned through a certain angle, the line may be brought back into the confines of the second slit, and from the angle itself one can easily infer the velocity of the flocculus along the line of sight.

In this way Hale analyzed the hydrogen filaments, viz. the prominences projected on the disc, and the rapid descent of the hydrogen towards the surface was observed and measured. Similar measurements may be effected with Deslandres' *spectro-enregistreur des vitesses*: with this instrument maximum velocities were measured of about 400 km/sec as have been observed in the case of prominences.

The other class of regular displacements that are observed when the spectrum of the limb is compared with that of the centre of the disc, paves the way to determining solar rotation at the latitude towards which the slit of the spectroscope is directed and at the level of the line under observation. This method of measuring solar rotation is far more accurate than others which we have been permitted to study; moreover, it offers the advantage that the measurements may be extended to high latitudes where there are no spots, faculae or flocculi.

Since Vogel demonstrated the possibility of the method in 1871, several series of spectroscopic observations, both visual and photographical, have been carried out. Among the former we may note those effected by Dunér at Upsala from 1880 to 1890, and from 1901 to 1903, in which he took the atmospheric lines as standards of reference. He observed points of the limb, from the equator to $\pm 75^\circ$ of heliographic latitude, and concluded that Faye's formula, like the formulae of Spörer and Maunder (page 77), is the one that most closely represents his spectroscopic observations, including those made at high latitudes.

From 1903 to 1906 Halm at Edinburgh, applying the differential method as did Dunér, used a heliometer which, with its object-glass divided in two, enabled him to pass rapidly from one limb to the other and to obtain greater precision. His observations showed considerable systematic differences for the different years, so that they led him to conclude a possible variability of the period of solar rotation Variations certainly exist according to the level considered

with the various spectral lines examined, as a consequence of the disturbances in a particular region of the sun, but any changes in the duration of the cycle of solar activity are not so easily proved, especially if we are comparing series of observations made with different instruments and at different places. As we shall see, the results hitherto obtained do not yet permit us to conclude a definite and precise law.

These preliminary visual observations have been superseded entirely by photographic observations, with the advantage of permitting measurements of a large number of lines on the plates and extending the researches to cover a larger region of the spectrum. Among the first photographic determinations are to be noted the classical series executed by Adams in 1906 and 1908 with the horizontal and vertical telescopes of the Mount Wilson Observatory, where later the observations were and are still continued systematically.

In his first measurements of 1906–7 Adams used the Snow telescope in conjunction with a spectrograph of 5·5 m focal length and a Rowland grating. On the slit of the spectrograph two small prisms giving total reflection were mounted at a distance apart equal to the diameter of the solar image; immediately above the slit two other prisms received the light from the first two and reflected it through the slit inside the spectrograph. In this way it was possible to compare directly the two opposite solar limbs side by side, and since the support of the prisms was capable of rotation, the two outside prisms could be set at any latitude on the solar limb.

When the dispersion curve of the prisms or of the grating has been established, the shifts of the lines as measured in millimetres with the spectrocomparator must be reduced to angstrom units, and these multiplied by the velocity of light (expressed in km per second) and divided by the wavelength of the line examined (also expressed in angstroms) give the desired velocity in kilometres per second.

In order to obtain from these linear velocities those actually corresponding to the period of sidereal rotation of the sun at different latitudes, it is necessary to allow for certain corrections which are easily calculated by employing the special data for physical observation of the sun which the *Nautical Almanac* and the *American Ephemeris* state each year, day by

day, together with the new tables published recently by Zagar, which supersede the antiquated tables of Dunér. With the above-mentioned ephemeris and tables, we first calculate the corresponding latitude from the position angle at which the slit has been directed, and then the two corrections necessary for passing from the measured velocity at that latitude to the actual velocity of rotation.

The first correction concerns the fact that the measured velocity contains the component of orbital motion of the earth along the line of sight. In order to change over from synodic to sidereal velocity it is necessary to add to the observed velocity an amount that is found in the above-mentioned tables for the corresponding date of observation.

The second correction concerns the fact that we do not measure the actual velocity of the point considered but only the component of that point along the line of sight, i.e. along the perpendicular to the plane of the apparent disc. Only when the solar pole happens to be on the limb do we measure the entire velocity of the point considered, because in that case all points on the limb are moving perpendicularly to its plane. This correction, too, is given in Zagar's tables as a function of the heliocentric latitude of the earth. Strictly speaking, there would be another correction of the same nature as that due to the orbital motion of the earth, depending on the component of diurnal motion of the observer along the line of sight. This correction, however, is at the utmost two-thousandths of a kilometre per second; therefore, since the observations (even those effected with the most powerful instruments and under the best conditions) do not succeed in establishing the mean velocity with an accuracy of one-thousandth of a second, the correction can generally be neglected.

Up to now we have been considering that the observations should be carried out on the limb itself, but if they are effected at points further inward, as is usually done to avoid the trembling of the limb due to our atmosphere and diffused light, the velocity obtained will be smaller, and in order to reduce it to the value that would apply if it had been observed at the limb, it must be multiplied by the secant of the angle contained between the sun's radius, produced to the particular

point on the disc at which the observation is made, and the perpendicular to the line of sight.

The linear velocity v, corresponding to the sidereal period of rotation, is measured and gives a basis for calculating the diurnal angular velocity ξ for a particular latitude, as we have seen is done in the case of sunspots (page 81). As a matter of fact ξ is obtained by multiplying v by 360° and by the number of seconds contained in one mean solar day, and then dividing this product by the number of seconds of the sun's circumference (expressed in kilometres) for the cosine of the latitude.

In the researches of 1908 Adams used the 60-foot solar tower of Mount Wilson, with object-glass of 18 m focal length, in conjunction with a collimator spectrograph of 9 m focal length, which, in third order spectrum, gave him 1 mm = 0·56 A on the plate. He measured the velocity v at latitudes 0°, 15°, 30°, 45°, 60°, 75° for a score of lines of the reversing layer between 4200 A and 4300 A, belonging to the G band and also to the head of the first cyanogen fluting having intensities between 1 and 4 on Rowland's scale. Besides these lines Adams studied in particular the velocities given by the blue line of calcium at 4227 A and by $H\alpha$.

The results of these important measurements by Adams may be summarized as follows: The two series of measurements made in 1906, 1907, and 1908 are in good agreement with each other and with the previous observations by Dunér. Both these series show that not only the lines of the various elements give different values for the rotational velocity, but also that, for lines having systematically large or small velocity-values, the largest deviations are obtained between moderate and high latitudes.

The lines showing the greatest divergence from the mean values of angular velocities are set forth in the table opposite together with the actual deviations divided into two groups, of high and low latitude, and at the heights presumably attained by these lines in the chromosphere as derived from the chromospheric arcs (page 246) during total eclipses.

The hypothesis which appears to give the most natural explanation of these deviations is that they are due to an effect of level, so that elements occupying a relatively low

level in the solar atmosphere have correspondingly low values for the angular velocity of rotation, or, in other words, that the outer layers of the solar atmosphere move more rapidly than those situated close in. This phenomenon generally holds good for large differences of level, but in the case of small differences (and hence in the actual reversing layer), the phenomenon seems to be more complex than a simple effect of level, and it will more likely be necessary to establish the relationship between the velocities and the energy levels of the lines in question, dealing with them as multiplets and thus endeavouring to separate any effect due to the different

λ *Rowland Revision*	*Element*	*Height on the photosphere*	*Latitude*	
			0°–20°	60°–80°
		Km.		
4196·547	*LaII*	500	− 0·1°	− 0·3°
4197·102, 4215·978	*CN*	500	− 0·1	− 0·3
4257·663	*Mn*	400	+ 0·1	+ 0·3
4226·742	*Ca*	5000	+ 0·4	+ 1·6
6562·816	*Hα*	11,000	+ 0·6	+ 2·8

intensities of the individual lines, which intensities depend in turn on the height of the layer on the photosphere.

The results for the *Hα* line were deduced by Adams from series of observations made at the various latitudes, either at the limb itself or three millimetres inside it, in order to ascertain what effect the reduction of the wings of the line has on the velocity. Comparison between the results obtained shows that the points nearest the limb not only give higher absolute values but also a smaller variation of velocity with varying latitude. An effect of this kind was to be anticipated in view of the fact that the level of actual absorption for points near the limb, in the case of an element like hydrogen, must probably be situated higher than for points inside the limb. The determinations carried out with the calcium line 4227 A also show that the vapour of neutral calcium moves, like hydrogen, more rapidly than the reversing layer and with less variation of velocity than the reversing layer

at increasing latitude, and that the velocity for the K_3 line of ionized calcium is still greater.

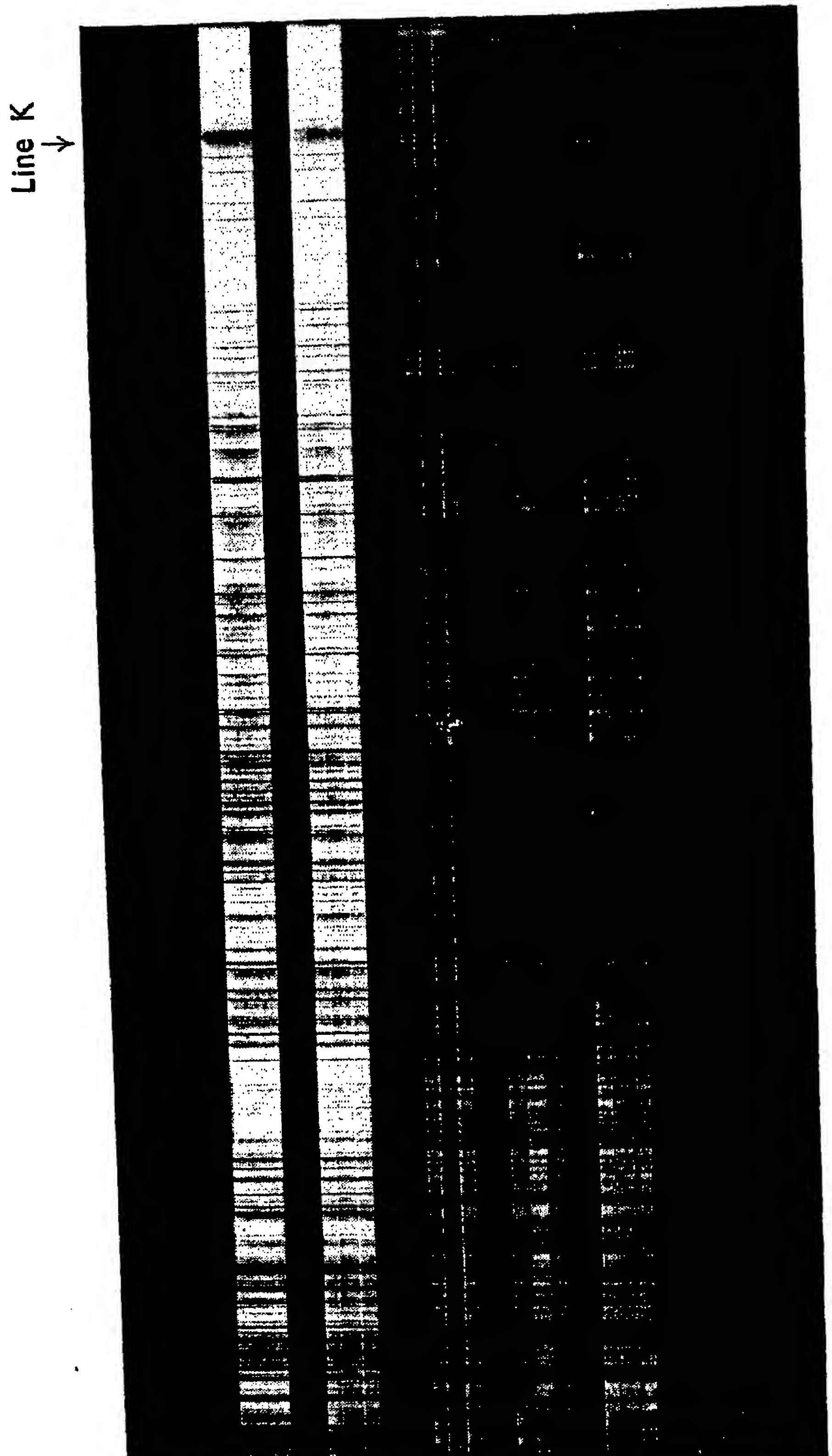

FIG. 84. Spectra for the study of solar rotation in the reversing layer (Arcetri).
(Each spectrum is obtained by comparing the eastern equatorial limb with the western equatorial limb: the Doppler effect is visible.)

But the results obtained (page 130) from the movement of calcium flocculi and those obtained at Arcetri by measuring the Doppler effect for the components $H\alpha_2$ and $H\alpha_3$, the slit

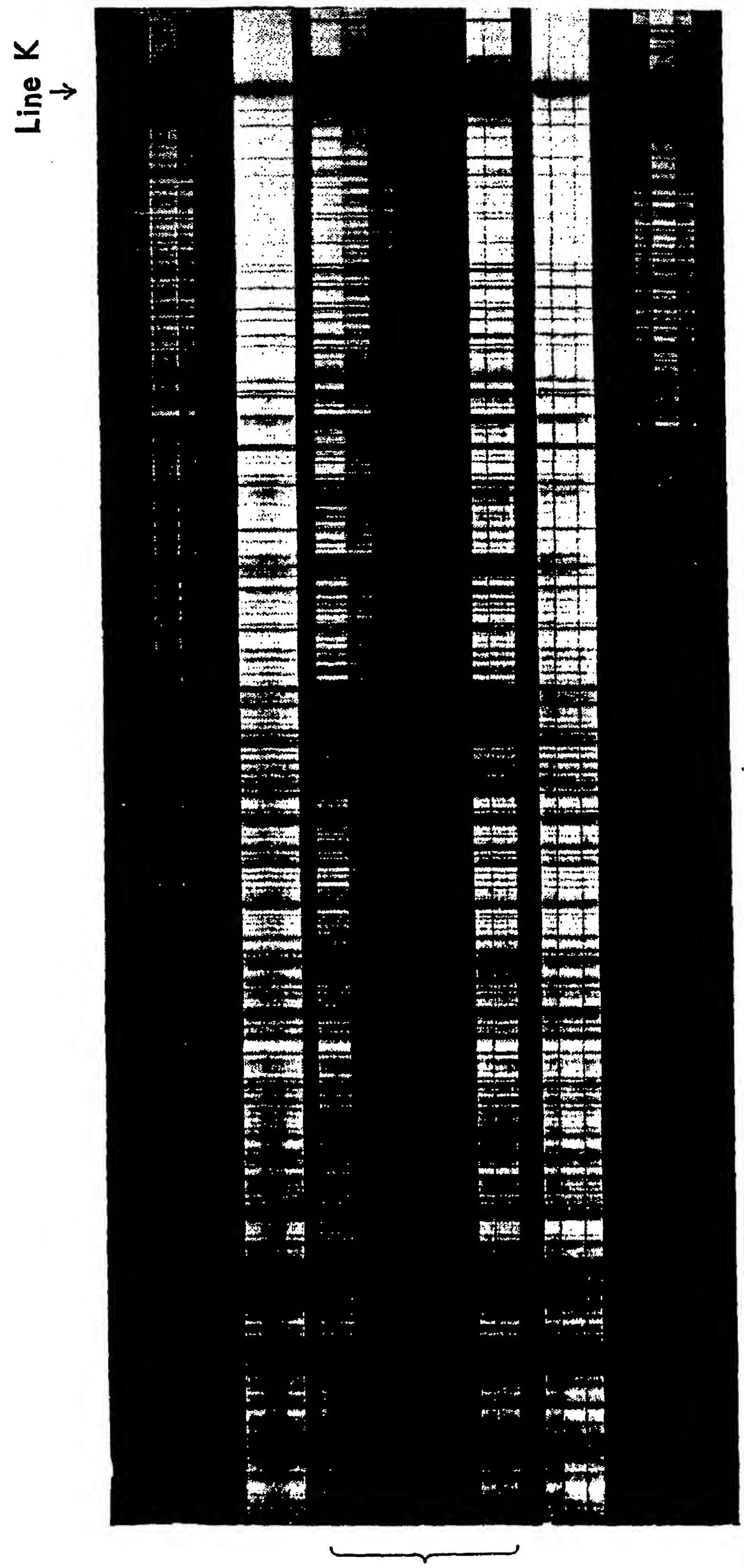

FIG. 85. Spectra for the study of solar rotation in the reversing layer (Arcetri).

a, *b*, *e*: Spectra of the equatorial limb and of the centre of the disc.; *d*: Spectrum of the eastern and western limbs; *c*: Spectra obtained with a graduated filter for photometric calibration of the plate.

of the spectrograph being placed tangentially to the solar limb, are not in agreement with previous results, since both for flocculi and for the components $H\alpha_2$ and $H\alpha_3$ a law

of rotation is obtained which comes nearer to that of the reversing layer and of sunspots than to that obtained by Adams for *H*α and by St. John for K_3.

Summarizing the results arrived at by the various direct or spectroscopic methods, we obtain the following table:

ϕ	*Spots*	*Faculae*	*Calcium flocculi*	*Reversing layer*	*4227A Mount Wilson*	*H*α_2 *Arcetri*	*H*α_3 *Arcetri*	*H*α *Mount Wilson*	K_3 *Mount Wilson*
°	°	°	°	°	°	°	°	°	°
0	14·4	—	14·5	14·2	15·1	13·9	14·7	15·2	—
15	14·2	14·3	14·3	14·1	14·8	—	—	14·9	15·5
30	13·7	13·8	13·9	13·5	14·3	11·9	13·6	14·5	—
45	—	12.8	13·2	12·6	13·6	—	—	14·0	15·4
60	—	—	—	11·5	12·5	9·1	10·9	13·5	—
75	—	—	—	—	13·3	—	—	14·2	—

In this table the values for sunspots, faculae and flocculi are those already given on pages 77, 81, and 130; those for the reversing layer are derived by forming the average of the most trustworthy measurements effected from 1906 to 1929, the rotational velocity in that period being assumed to be constant. The values for the components *H*α_2 and *H*α_3 are obtained from measurements effected at the Arcetri solar tower in 1928, those for *H*α at the limb, and the lines 4227 A and K_3 from the measurements by Adams and St. John referred to above.

The fact is to be noted that both for 4227 A and for *H*α there is a sudden increase of angular velocity between 60° and 75° latitude. It should be remembered that at high latitudes the angular velocity is extremely sensitive to small differences in linear velocity, because, for instance, a variation of 0·018 km/sec at 75° reduces the value of ξ from 14° to 13·5°, so one should not attach too much importance to the increase found, which might be due to errors of observation and measurement. Nevertheless, in view of the fact that a similar trend has been noted by Adams for the various lines of the reversing layer, it would seem that there is indeed some agency which tends to increase the angular velocity near the solar poles in the highest zones of its atmosphere.

The values in the foregoing table have been plotted in the graph (Fig. 86), and this graph shows clearly the law of the

rotation associated with the various phenomena. The reversing layer and the emission components $H\alpha_2$ give the lowest velocities and the greatest equatorial acceleration. Then come, with gradually increasing velocities, the spots, faculae and flocculi, until at the highest level, represented by the component K_3, the velocity is highest and almost constant. In the hypothesis of levels it is not clear how this trend, which is contradictory as regards the level assumed for sunspots, can be accounted for with reference to the trend of the reversing layer and of hydrogen as found by measurement of the various $H\alpha$ components.

A theory (Wilsing) has been propounded regarding the existence in the sun of layers rotating at a constant angular velocity and comprising layers having an angular velocity that varies with latitude. Or it may be presumed that the various absorption and emission lines observed at the solar limb are more or less under the influence of the low level at which they originate. Further observations will obviously be necessary in order to explain this trend.

Besides the spectroscopic determinations of the sun's rotation which we have described, many others have been carried out and the differences between the mean values found at different epochs by the various observers suggest a possible variability of the period of rotation, perhaps in relation to the eleven-year cycle.

Newall, discussing observations carried out from 1901 to 1913, finds that Faye's formula:

$$v = (a - b \sin^2 \phi) \cos \phi$$

satisfactorily sets forth the variation of velocity with latitude resulting from observations by Dunér, Halm, Adams, Plaskett, De Lury, Schlesinger, but that, on the other hand, both a and b may vary during the course of the eleven-year cycle; furthermore, that the value of b may be different at a certain epoch, in different parts of the same hemisphere. At the actual minimum period of sunspots the vapours on the sun's surface, at about 50° latitude, lag behind those of adjacent zones of latitude with a maximum retardation ($b = 0{\cdot}7$ or $0{\cdot}8$). At the same time the equatorial vapours move at their lowest velocity ($a =$ about $1{\cdot}94$ km/sec) but then begin to regain

speed when the spots at the equator are disappearing. The critical relative velocity between adjacent zones of latitude is attained at an angle of about 40° with the appearance of spots in these latitudes.

At the maximum sunspot period, a attains the maximum value of about 2·07 km/sec.

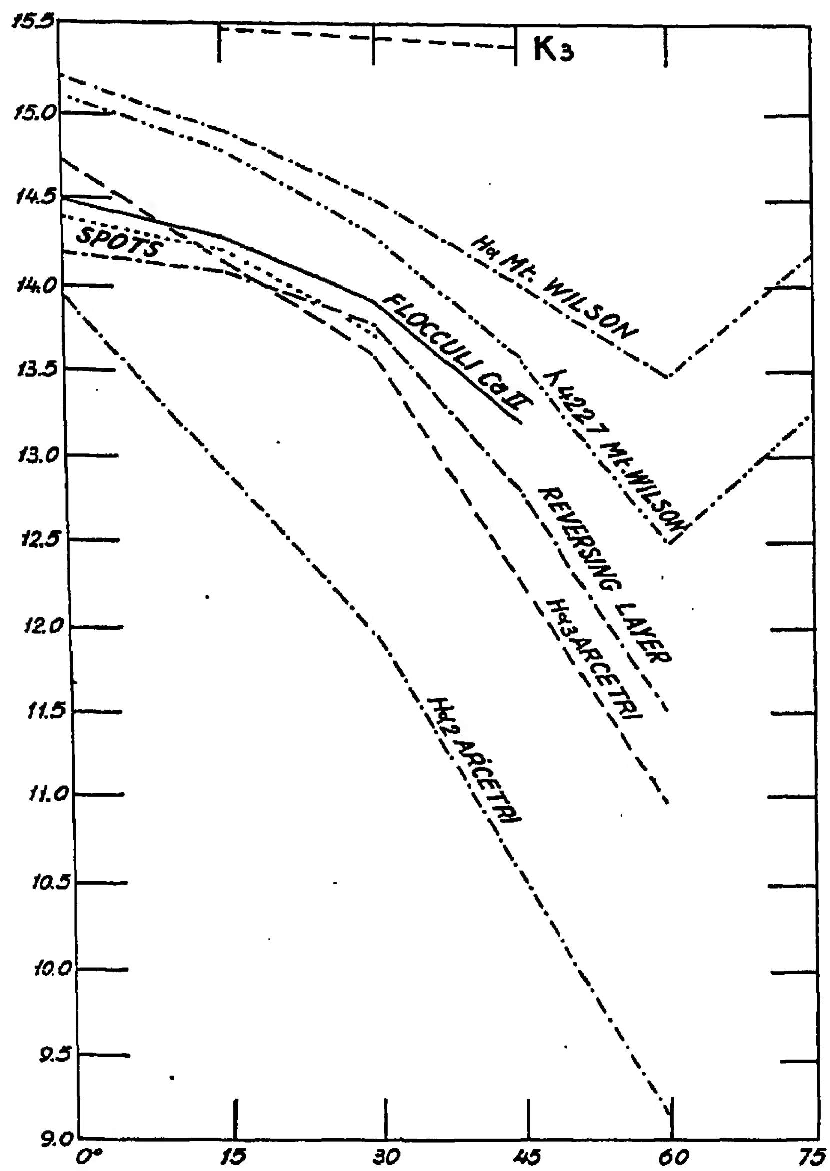

FIG. 86. Comparison of the angular velocities of various solar phenomena.

As, however, the observations discussed by Newall cover one cycle only and were carried out with different instruments and by different methods, no certain conclusions can be drawn from them as to variability of the rotational period.

In order to have a series of homogeneous observations carried out with one instrument and by the same method,

observations similar to those made by Adams were commenced as early as 1914 with the solar tower at Mount Wilson, and are continued regularly. Since that same year similar measurements have also been carried out at Edinburgh; they are always made by the same observer, using the same instrument. The results obtained at these two observatories, gathered in two-yearly averages from 1915 to 1931, do not show very good agreement, nor can we, by combining the two series, draw any definite conclusion throwing light on possible periodic variations, as will be seen from the following table:

Year	*Linear velocity at the solar equator in km/sec.*	
	Mount Wilson	*Edinburgh*
1915	1·94	1·92
1917	1·93	1·96
1919	1·92	—
1920	—	2·00
1921	1·91	1·98
1923	1·90	2·03
1924	1·90	—
1925	—	1·97
1927	—	1·98
1929	1·91	1·98
1930	1·95	—
1931	—	1·97

Since the error of each of these values should be less than 0·01 km/sec, there must evidently be some systematic error causing discrepancies between the two series of observations.

With regard to those of Mount Wilson it may be noted that they are effected with a powerful instrument, the 150-foot tower in conjunction with the 75-foot spectrograph. Moreover, simultaneous observations have been purposely carried out for the sake of comparison between the 150-foot tower, the Snow telescope and the 60-foot tower, and it has been found that within the established limits of precision the three instruments give concordant values, which should ensure homogeneity and the possibility of directly comparing these most recent measurements with those of Adams of 1906–1908

referred to above. The results of the period from 1914 to 1932 in conjunction with the previous observations of Mount Wilson, which give an average velocity of 2·06 km/sec at the equator, would seem to suggest a variation of such a nature that it cannot be accounted for by errors of observation.

On the hypothesis that the sun's rotation, deduced from spots, is a measure for the rotation of the photosphere, the linear velocity of the reversing layer in 1906 was 0·06 km/sec greater than that of the photosphere, in 1918 0·10 km/sec less, and attained in 1925 a long minimum, the period then becoming two days longer than in 1906. From 1928 onwards the Mount Wilson observations show a fairly regular increase of velocity which, however, until 1932, remains below that of the photosphere. St. John believes that these variations may be interpreted as being caused by long-period drifts of the reversing layer, which succeed each other alternately towards the east or towards the west, thus accelerating or retarding the period of solar rotation.

If, on the other hand, instead of taking the results of one observatory, we collect the more numerous results obtained in recent years in different observatories and with different instruments, and then take the averages of these results without allowing for systematic differences which, as seen at Mount Wilson and Edinburgh, certainly do exist, we obtain the summary given on p. 171.

From the examination of these values it would appear that from 1909 to 1912 there has been a rapid and considerable diminution of the linear velocity and hence an increase of the rotational period at the equator of about one day.

From theoretical considerations it may be inferred that a progressive variation is highly improbable, because the loss of mass as a result of the loss of luminosity is too small to be observed in so short a time. It is more probable, on the other hand, that there is a periodic variation in relation to the frequency cycle of sunspots, or, as we shall see, to that of their polarity. For the first cycle the period should be eleven years, but neither spectroscopic observations nor observations of long-lived spots (which give for the last thirty years a constant value of 2·02 km/sec at the equator) show such a periodicity. For the second cycle the period should be double, viz. from

22 to 23 years; this fact might be suspected from the values quoted in the following table.

There would thus seem to be variations of linear velocity in relation to the change of polarity actually occurring at each of the two eleven-year cycles (page 214), which might produce in the reversing layer currents directed towards the east in

Year	*Linear velocity at the equator in km/sec.*	*Authority*	*Observatory*
1900	2·05	Dunér	Upsala
1906	2·05	Halm	Edinburgh
1908	2·06	Adams-Lasby	Mount Wilson
1909	2·08	Storey-Wilson	Edinburgh
1912	1·97	Plaskett-De Lury, Hubrecht, Schlesinger	Ottawa, Cambridge, Pittsburgh
1914	1·95	Evershed, Royds, Plaskett, St. John-Ware	Kodaìkanal, Ottawa, Mt. Wilson
1916	1·94	Plaskett, St. John-Ware	Ottawa, Mt. Wilson
1918	1·94	St. John-Ware, Storey	Mt. Wilson, Edinburgh
1920	1·95	St. John-Ware, Storey	Mt. Wilson, Edinburgh
1922	1·95	St. John-Ware, Storey	Mt. Wilson, Edinburgh
1924	1·93	St. John-Ware, Storey	Mt. Wilson, Edinburgh
1926	1·96	Beloposky, Storey	Poulkovo, Edinburgh
1928	1·95	St. John-Adams, Beloposky, Storey	Mount Wilson, Poulkovo, Edinburgh
1930	1·93	St. John-Adams, Abetti-Novàkovà, Righini Freundlich, Beloposky, Storey	Mount Wilson Arcetri, Potsdam, Poulkovo, Edinburgh
1932	1·95	Evershed, Perepelkin, Storey	Ewhurst, Poulkovo, Edinburgh

one eleven-year cycle and towards the west in the next cycle, which confirms what we can infer from the observations of Mount Wilson alone.

It will be necessary to await future observations in order to ascertain whether, in years to come, the suspected variations will indeed be confirmed in a more definite manner or whether, on the contrary, we shall have to conclude that the period of solar rotation is constant. For the time being it may be noted that:

(*a*) the various Fraunhofer lines, on account of their different

intensities, their different energy-levels, the spectral region to which they belong, or other causes due to the superposition of other lines, etc., give widely divergent velocity values;

(*b*) different instrumental conditions and different observers may give values which are not concordant within the limits of errors in observation, indicating the presence of systematic errors due to the size of solar image used and to the point of the limb observed;

(*c*) with the same instrument and the same observer, non-concordant values may be obtained, probably because of atmospheric conditions (transparency of the sky, diffused light, tranquillity of the solar limb).

Under these circumstances, considering that by averaging the values obtained by different observers with different instruments, as has become possible in recent years (page 171), increasingly concordant results are obtained in which it is difficult to discern a variation of any importance, it would seem reasonable to conclude that the variability of the period of solar rotation is, at least for the present, problematic, and that at any rate one will in future have to compare results, taking into account the circumstances mentioned, while endeavouring as far as possible to increase the precision of the observations and to render them free of systematic errors.

Radial Movements in Sunspots and Circulation in the Solar Atmosphere

The vortex structure of the hydrogen flocculi which are often found in the interior of sunspots and which led Hale to the discovery of their magnetic fields, would suggest that, together with hydrogen, metallic vapours also are drawn into the vortex movement around the axis of the spots. But, remembering that in the solar atmosphere these metallic vapours and hydrogen are distributed at very different levels, there is reason to suppose that both the general circulation and the particular circulation superimposed upon the spots may differ very greatly. As a matter of fact Evershed, at the Kodaikanal Observatory in South India, when investigating possible displacements due to the Doppler effect in sunspots, discovered in the Fraunhofer lines across the umbra and penumbra certain deformations which varied with the orien-

tation of the spectrograph slit on the sunspot and with the position of the latter in relation to the centre of the solar disc. These deformations are now known as the "Evershed effect"

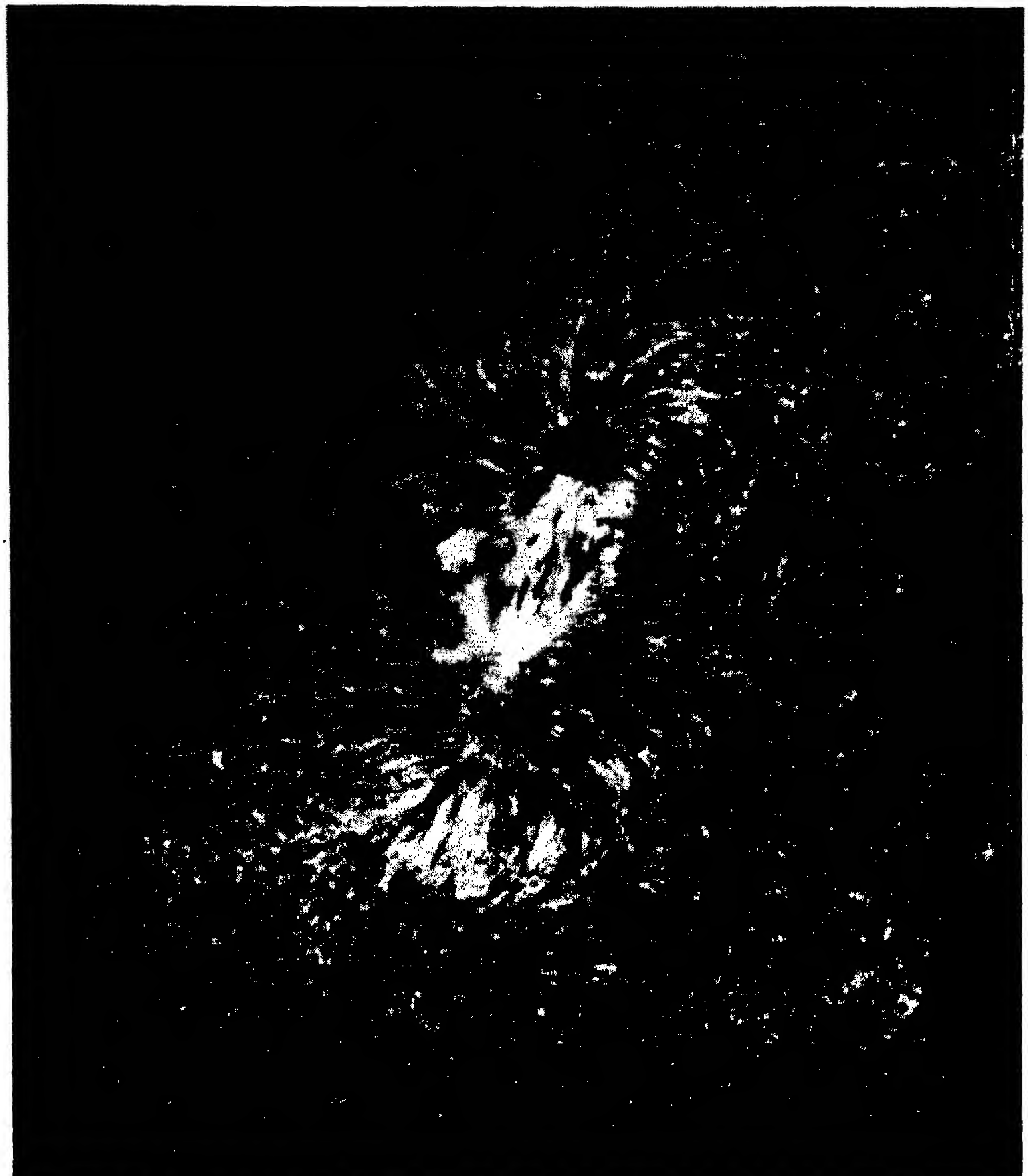

FIG. 87. Group of sunspots with vortex structure.
(Spectroheliogram in hydrogen light [$H\alpha$], August 30, 1924, Mount Wilson.)

and are believed to be due to a movement of metallic vapours receding from the spots, radially from their centre and parallel to the sun's surface.

The phenomenon may be observed in most sunspots when

the slit of the spectrograph is placed on the umbra and penumbra in the direction of the sun's radius ("radial slit"). If the spot is not exactly at the central meridian, but about 10° beyond, it is found that the Fraunhofer lines of medium and faint intensity are inclined with respect to their normal position, so that at one edge of the spot they appear to be shifted towards the red and at the other edge towards the violet. The displacements are of opposite sign from opposite parts of the central meridian and, in the vast majority of cases, are directed towards the violet at the edge of the preceding spot, viz. at the western edge, and towards the red at the following edge, if the spot is at the east of the central meridian; if, however, it is at the west, the displacements are reversed. It makes no difference whether the spot is in the northern or southern solar hemisphere.

If the slit is directed at other position angles, or if it is set entirely perpendicular to the radial direction ("tangential slit"), it will be noticed that the displacements generally diminish and sometimes vanish altogether.

The simplest hypothesis that can be propounded to explain the facts observed is, as already mentioned, that the metallic vapours which are superimposed on the umbra and penumbra possess a radial motion from the centre to the exterior of the spot, approximately horizontal or parallel to the sun's surface, which would account for the total disappearance of the deformations of the lines when the spot approaches and passes through the central meridian. The fact that the displacements are always least when the slit is placed tangentially on the spot, indicates that the component of the vortex motion is always less than that of the radial motion.

From the inclination of the lines on the spots, Evershed also infers that the movement from the umbra to the spots towards the exterior is accelerated, attaining a maximum of about 2 km/sec at the outermost edges of the penumbra. All this applies to the metallic vapour lines of medium intensity, but on examining the lines H_3 and K_3 of the high chromosphere we find in the penumbra distortions analogous to those described, but in exactly opposite direction, viz. towards the violet at the edge of the spot that is directed towards the solar limb. This means that the calcium vapour of the high

atmosphere flows towards the centre of the spots with an analogous motion but in the reverse direction to the motion of the metallic vapours.

The researches of Evershed were followed by those of St. John at Mount Wilson with the 60-foot tower in 1910 and 1911. He determined the displacements for a considerable number of absorption lines, so that a statistical treatment may be made of the various lines, according to their level, from the highest layers of the chromosphere with lines H, K, *Hα*, to the less high layers represented by the most intense lines of magnesium, aluminium and iron, down to the faintest lines of the lowest levels. Whereas Evershed determined the dis-

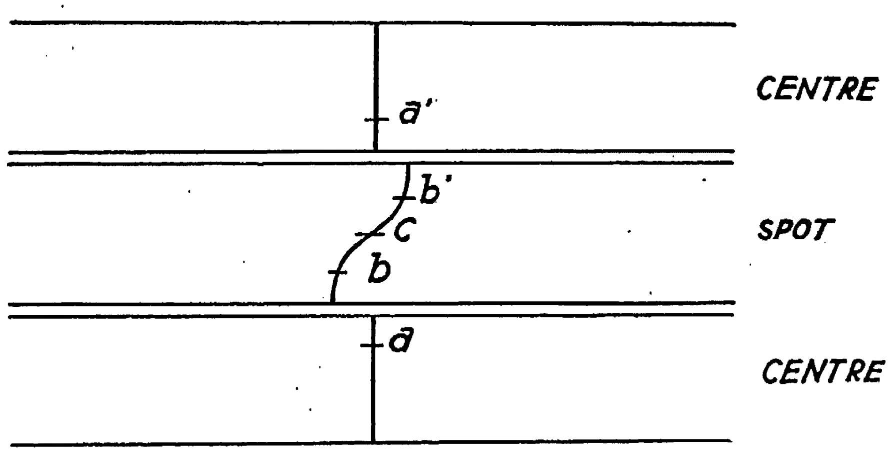

FIG. 88. Typical distortion of the lines of the reversing layer on sunspots (Evershed effect).

placements of the lines by reference to the spectrum of the photosphere immediately outside the zone disturbed by the spot, St. John measures them by comparing the two opposite edges of the penumbra, photographing them with a screen in such a manner that the two edges are made to appear side by side and hence the double shift obtained.

The observations of St. John substantially confirm Evershed's hypothesis and show, moreover, that since there exists a proportionality between the shifts and the wavelength, the phenomenon is indeed due to the Doppler effect with efflux of materials of the reversing layer from the interior and from the centre of the spots, whilst the chromospheric material flows towards the centre and towards the interior of the spots.

The outward velocities increase gradually according to the distance below a mean level, where the speed is zero, and

the inward velocities increase according to the height above the mean level, which may be called the inversion level of the velocity.

Summarizing the results found, St. John traces a diagram representing the direction of motion and the velocities of the vapours at various heights on the spots and for lines of different intensities (Fig. 93, page 186).

The lines giving the mean radial velocity of recession from the centre of the spot of 1 km/sec are the faintest, having an intensity of about 0 in Rowland's scale; the lines that are at the neutral level have an intensity of 10 to 20, and those giving the velocity of approach are the most intense of the solar spectrum.

A general convective ascending motion for the lowest vapours and of descending motion for the highest, also found by St. John, is, as we shall see later when comparing the spectrum of the centre with that of the limbs of the sun, likewise drawn in the diagram, which furthermore indicates the vortex superimposed on the spot and visible only in the hydrogen atmosphere.

St. John propounds the hypothesis that the lines of lesser intensity may be produced in the lowest layers of the solar atmosphere, and hence the direction and velocity of the flux might be considered as a function of the depth. According to this conception the real level of a line may be defined as that portion of the total thickness of a particular gas which takes the greatest share in producing the line. For example, the absorption given by a Fraunhofer line of intensity 4 in Rowland's scale originates from a greater depth than a line of intensity 10.

The light from the photosphere and from the lowest and hottest layers of the vapour under consideration is absorbed selectively in the two cases and cannot reach the surface, so that the light emitted by the respective wavelengths originates from more or less defined layers of vapour with a greater radius for the line of intensity 10 and a smaller radius for the line of intensity 4. As we have seen (page 111), the idea of these effective levels has been conceived in order to explain the spectroheliograms obtained with the various parts of one and the same line and is fully confirmed by the trend of these

radial movements and by the vapour-height determinations (page 245) that can be effected during total eclipses.

A comparison of these determinations, as given by Mitchell, with the motions determined by St. John for the iron lines, is reported in the following survey, in which are also set forth the average excitation potentials of the various groups of lines measured:

Intensities of the lines (Rowland)	0–2	3–5	6–8	9–12	15–40
Height of the chromosphere in km (Mitchell)	330	440	600	940	1450
Evershed effect in km/sec (St. John)	1·7	1·2	0·8	0·2	0·1
Excitation potential (in volts)	3·30	2·86	2·20	1·66	0·87

When discussing the radial displacements St. John also notes that they are greater in the red than in the violet for lines of the same intensity. This may be ascribed to the fact that our means of observation attain a greater depth in the red because of the diffusion of violet light, so that the real levels are lower for the larger wavelengths.

In conclusion of these researches by St. John, combined with the results obtained during eclipses, it may be stated that the vapours of the various elements ascend in observable quantities at different heights; that the lines of a given element originate at increasing depths with diminishing intensity; that the enhanced lines show a higher level than neutral lines of the same intensity; that we can look into the sun to a greater depth at the red end of the spectrum than at the violet end. The resulting distribution shows that the lines H_3 and K_3 of ionized calcium are those of the highest level, followed by the line $H\alpha$ of hydrogen, and that in general the heavy and rare elements are present in observable quantities only in the lowest regions of the solar atmosphere.

The phenomenon of the prevailing "radial motion" of the vapours in conjunction with the "tangential motion" is certainly very complex, as may be inferred from the observations described, and it will be desirable to carry out further systematic observations on spots of different sizes and degrees

of activity, at different heliographic co-ordinates, during the various cycles and to examine spectral lines of different types, in order to arrive at a more satisfactory explanation of the various characteristics.

In the last maximum of sunspots, viz. from 1926 to 1932, a series of observations with the solar tower at Arcetri was effected to this end. Deviating from the methods followed by previous observers, the maximum displacements b and b' of the lines on the spots were determined and compared with points a and a' of the same lines photographed at the centre of the sun's disc (Fig. 88, page 175). From the results obtained in this way, the observations being carried out only at times when there was no disturbance at the centre of the disc, it would seem that the displacements, corrected for the effect of solar rotation, are related to normal conditions of the sun, whilst the regions of the photosphere in the immediate vicinity of spots are practically always disturbed. During the period mentioned some thirty spots were observed in the two positions of the slit, radial and tangential, and were followed as far as possible in the course of their rotation; moreover, from spectroheliograms taken simultaneously or almost simultaneously, a study was made of the appearance of hydrogen vortices around the same spots.

The results obtained at Arcetri lead to conclusions which differ slightly from those drawn from previous studies, the chief conclusion being that the Evershed effect cannot be described as constant and regular for all sunspots. As a matter of fact the speeds of efflux of metallic vapours are highly variable, ranging from very low speeds, near zero, to a maximum velocity of about 6 km/sec for the radial components. The tangential components are much smaller than the radial ones but are nearly always measurable, attaining in this series of observations a maximum speed of about 3 km/sec.

It is to be further noted that, as seen in the foregoing table, St. John found a well-defined relation between the Evershed effect, the excitation potential and the chromospheric heights, so that, since the first of these factors is an indication for the various layers of vapours on the sun's surface, the second may be so too. Since, in the lines and multiplets considered by St. John, the intensity of the lines diminishes continuously

with increasing excitation potential, the two results are a consequence of each other. On the other hand, in the various groups of lines measured at Arcetri, consisting for the most part of multiplets, the relation between the intensity of the lines and the excitation potential (Fig. 90) for a variation of the latter factor greater than that of St. John's measurements, is not a linear one, and hence there is no linear relation between the potentials and the speed of efflux.

On the other hand, the relation between the intensity of

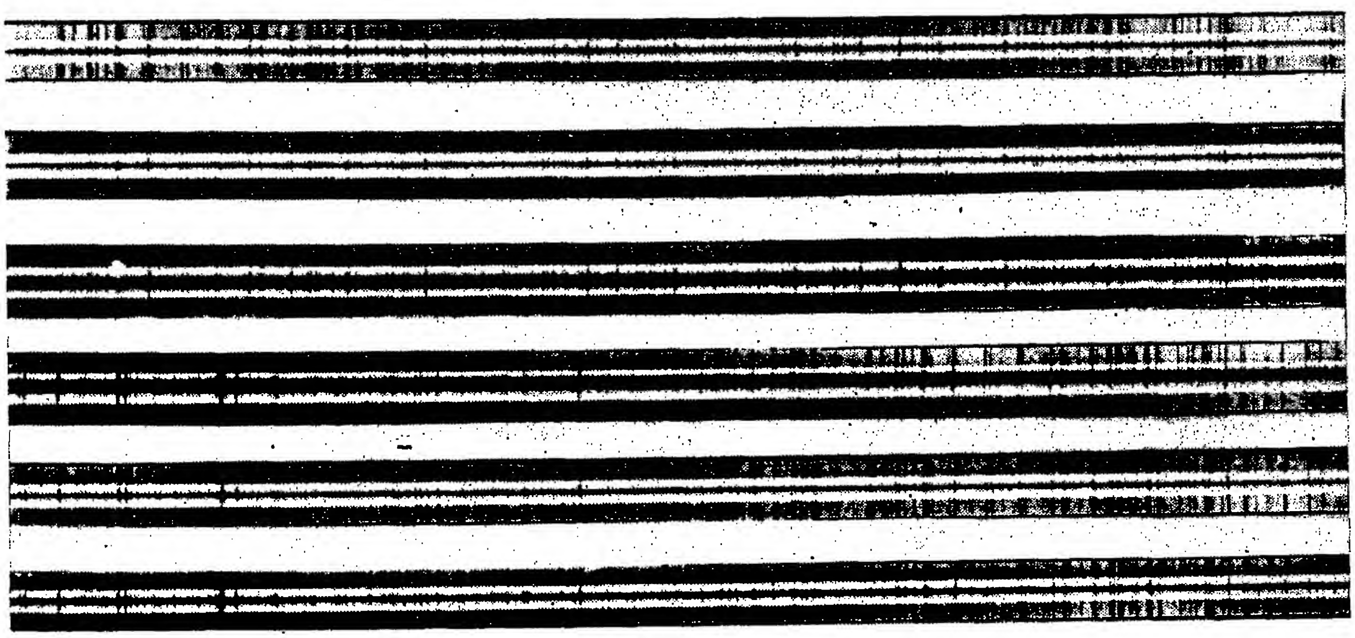

FIG. 89. Spectra of a spot compared with spectra of the centre of the sun (August 1, 1927, Arcetri).

(The central darkest band of each spectrum is due to the nucleus of the spot.)

the lines and the velocity (Fig. 92) shows a more regular trend of speed diminution for an increase of intensity of the lines, with a close agreement between the measurements of Mount Wilson and those of Arcetri, apart from a systematic difference due to the variable velocity of the vapours in the assemblage of spots examined at the two observatories. The rapid increase of velocity for the lines of mean intensity 1·5 measured at Arcetri, is due to four lines of ionized elements with an average excitation potential of 9·5 volts, belonging to chromium, scandium, titanium and iron, which are very intense in emission in the spectrum of the chromosphere and which attain, over the level of the photosphere, a height of from 600 to 800 km.

These heights being generally greater than those of most of the lines due to neutral atoms, they should give lower velocities than the mean. Considering, however, that these lines, in common with the generality of those due to ionized elements, become faint on sunspots, the maximum velocity found may be considered almost normal, as it proves to be more in accordance with the general trend given by the lines of greater intensity. This would suggest that in the intricate problem of these motions there is a kind of intensity equation

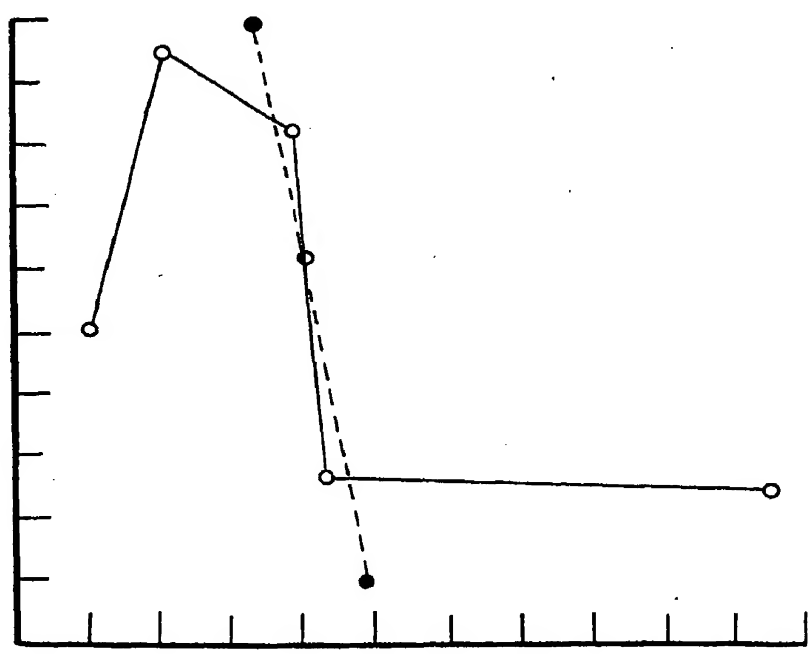

FIG. 90. Ratio between intensity of the lines (ordinates) and excitation potential (abscissae).

——o—— Arcetri ------●------ Mt. Wilson

depending on the real intensity that the lines possess on sunspots, not in the sense that the intense lines are measured in a different way from the faint lines, which has been proved to be improbable, but in the sense that the particular trend of the spectral line through the umbra, as may be seen in Fig. 89, is, as it were, rectified or attenuated as the intensity of the line increases.

In other words, this intensity equation would be superimposed on the real variation effect due to the ever-increasing levels of the photosphere.

In the complex of spots and lines examined at Arcetri the components of the radial motion average 1·5 km/sec and the tangential components about 1 km/sec, but one cannot really

speak of a mean value, because, as already stated, the motion of the vapours is very irregular and varies from spot to spot,

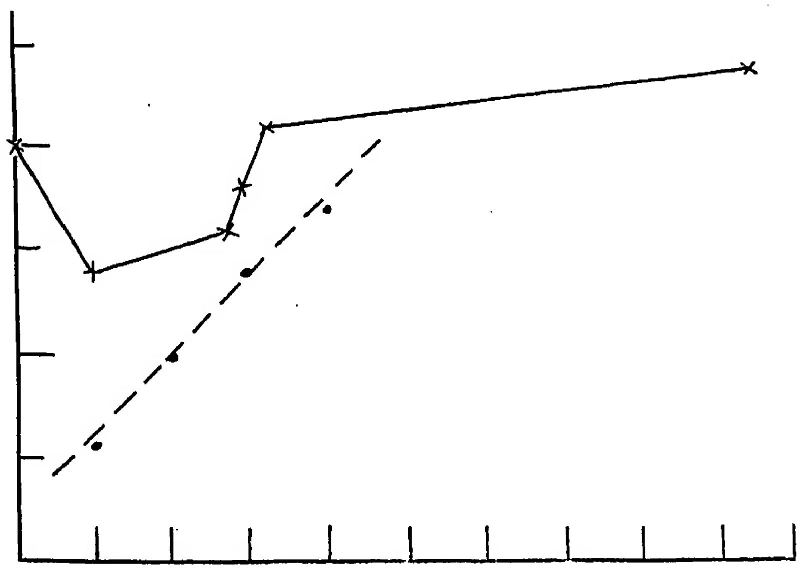

FIG. 91. Ratio between the velocity in km/sec. (ordinates) and excitation potential (abscissae).

———×———Arcetri ------------●------------Mt. Wilson

which seems plausible in the light of the proposed theory of their origin.

The colder masses of the photosphere, which constitute sun-

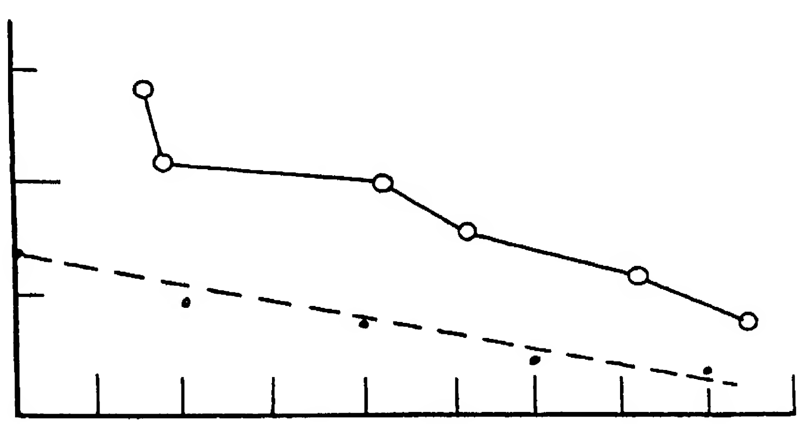

FIG. 92. Ratio between the velocity in km/sec. (ordinates) and the intensity of the lines (abscissae).

———○———Arcetri ------------●------------ Mt. Wilson

spots, are supposed by Bjerknes to be subject to continuous radiation from below, and the process of expansion that takes place on the nucleus continues to make the cooled masses emerge at such a velocity as to keep them sufficiently cold in spite of internal radiation. Now this process, by analogy with

the phenomenon of eruptions and prominences, will be more or less active and regular, as is demonstrated by the variability of the motions measured in both.

Moreover, it may be concluded from the present observations that, in contrast to Evershed's findings, the velocities are not a maximum at the outermost edges of the penumbra but at the edges of the umbra; in other words, the maximum deviation of the line from the normal position takes place at the boundaries between the umbra and the penumbra. In these observations at Arcetri it has been noticed that, in addition to the irregularity and variability of the absolute motion, there are also irregularities in the Evershed effect, because the radial components at the edges of the umbra have not always the sign claimed by Evershed; moreover, the reverse case may occur in which the outer edge of the spot (the edge directed towards the solar limb) gives negative components of approach and the inner edge gives positive components, or the case in which both components are of the same sign.

These cases generally occur when the nucleus of the spot is not single and regular, but double, or more or less complicated in general. When the Evershed effect is regular the two components may be of absolutely equal value, there thus being an efflux of vapours with the same velocity at both edges and in a direction parallel to the sun's surface, or the component at the outer edge may be larger in absolute value than that at the inner edge, in which case one may propound the hypothesis of a movement no longer parallel but inclined towards the sun's surface, and the mean angle of this inclination can be measured, it having been found to vary from 0° to a maximum of 30°. Sometimes, too, the component at the outer edge is smaller in absolute value than that at the inner edge, in which case it is evident that the hypothesis of an inclined motion no longer holds good, unless the axis of the vortex is considerably inclined towards the sun's surface, which, as we shall see from study of the Zeeman effect, is not probable. So we must conclude from these observations that, since the velocity of the motion is variable in absolute value, its characteristics are also irregular and variable and perhaps only attain the regularity claimed by the Evershed effect if the spot, in the course of its

evolution, assumes a simple and regular nucleus without convulsions or rapid transformations.

Convective Movements in the Solar Atmosphere. Einstein effect. Pressure effect. Limb effect

The first determinations of the wavelengths of the Fraunhofer lines in the solar spectrum, compared with corresponding determinations obtained in the laboratory, showed differences that were only partly explainable by the Doppler effect due to solar rotation. There must be other disturbing factors. It was thought that a pressure effect existed in the various layers of the solar atmosphere in which the Fraunhofer lines are produced; from direct comparisons with the lines of the arc, after elimination of displacements due to solar rotation, Jewell, Mohler, Humphreys, Fabry and Buisson, supposing that there were no other causes than those of pressure for making the lines shift, obtained various values between 5 and 7 atmospheres in the reversing layer.

Later researches, and the discovery of pole effect in the lines of the arc, demonstrated that these results were very erroneous. Evershed, Perot and Salet subjected to examination groups of lines with very different pressure coefficients, so that it was sufficient to know the differences of wavelengths instead of their absolute values. Moreover, this gives the advantage of rendering the result independent of the hypothesis that pressure is the only cause of displacements.

They thus found values lower than one atmosphere and fluctuating over a few tenths. Since, however, with the elimination of pole effect the differences between the pressure coefficients for the different types of lines were considerably reduced, a larger amount of data had to be collected in order to establish with precision the slight displacements due to pressure as was done at Mount Wilson by St. John and Babcock.

These observers took as a basis for their measurements the solar wavelengths in the international system, determined by means of grating spectrographs and interferometers, and in order to reduce the wavelengths to a vacuum they used the pressure coefficients also determined at Mount Wilson. More-

over, in order to eliminate as far as possible the effects on the wavelengths due to differences of level in the solar atmosphere, lines were observed having approximately the same mean intensity and hence belonging to about the same level.

Groups of lines were observed in the same spectral region in order to make the Doppler effect and the relativity effect negligible, and it was also proved that anomalous refraction cannot have an appreciable influence on the results. There were thus formed eleven groups of lines with different pressure coefficients, from which resulted the differences sun — vacuum and hence the pressure value in the layer to which the lines examined are due. The pressure values resulting from the different groups are inconsistent; the mean pressure referring to a layer of the solar atmosphere of some hundreds of kilometres above the photosphere, is found to be: $0 \cdot 13 \pm 0 \cdot 06$ atmospheres, thus indicating that the pressure in the reversing layer only attains a small fraction of an atmosphere. This explains the remarkable definition, in the sun, of lines which in the laboratory become broad and diffused even at moderate pressure. This low pressure in the reversing layer is in accordance with the pressures that have been calculated for the various levels of the solar atmosphere with indirect and theoretical methods.

From the theory of ionization (page 279), Saha infers that the ionization of calcium becomes complete at a pressure of 10^{-4} atmospheres. This should happen at the upper limit of the occurrence of neutral calcium, which may be estimated to be of the order of 5000 km from the line 4227 A.

From the increased intensity of the enhanced lines, St. John calculated that the pressure at the mean level is of the order of 10^{-1} to 10^{-2} atmosphere, and Russell finds that for metals and alkaline earths the increased intensity of the Fraunhofer lines, passing from 6000° of the photosphere to 4000° of the spots, is consistent with the percentage of ionization appropriate to pressures not exceeding 10^{-2} atmosphere in the absorbing layer.

Moreover, Russell and Stewart, discussing the various factors that may serve for determining the pressure of the sun's surface, such as the definition of the lines sensitive to pressure, the general opacity of the external regions, the absence of solar

light in the flash spectrum, the width of the Fraunhofer lines, the rotation equilibrium of the outer layers, the radiation pressure and the chemical equilibria existing in the solar atmosphere, conclude that the total pressure of the photospheric gases must be less than 10^{-1} atmosphere and that the mean pressure of the reversing layer does not exceed 10^{-4} atmosphere.

On the hypothesis that the vapour of *Ca*II is in equilibrium under the pressure of radiation and gravitation, R. H. Fowler and E. A. Milne find a mean pressure of the order of 10^{-13} atmosphere for a layer of this vapour between a height of 9000 km above the level of the photosphere and its upper limit, which, as already stated, is 14,000 km. On the basis of these results St. John and Babcock drew an interesting picture of the probable stratification of the elements, of the pressure and of the currents reigning in the solar atmosphere.

Fig. 93 indicates the elements found at the respective levels. Their heights are given in kilometres and the directions of the radial and vortex motions on sunspots and the convective motions on the disc are shown by arrows, while the respective velocities are expressed in km/sec. For the lines H and K of *Ca*II the tangential component of the vortex motion is indicated by a circle, the speed being measured in this case directly, while for $H\alpha$ it is based on the flux lines visible on the spectroheliograms. At the highest level that may be observed on the surface, ionized calcium flows in the spots at a speed of about 2 km/sec. At decreasing levels, hydrogen, ionized titanium, calcium, and neutral sodium also flow in the spots at increasingly low velocities. At the highest level attained by iron and aluminium the average velocity is zero; at lower levels the direction of the flux is reversed, as already stated, and the velocity towards the exterior increases as the height decreases.

The convective motions refer to the undisturbed solar disc, and have been ascertained by spectrographic integration over large areas of the surface, lines of different levels in the same spectral region being directly compared. The progressive increase of the differences may reasonably be explained as a consequence of ascending currents, accompanied by the corresponding descending currents on the sun's surface.

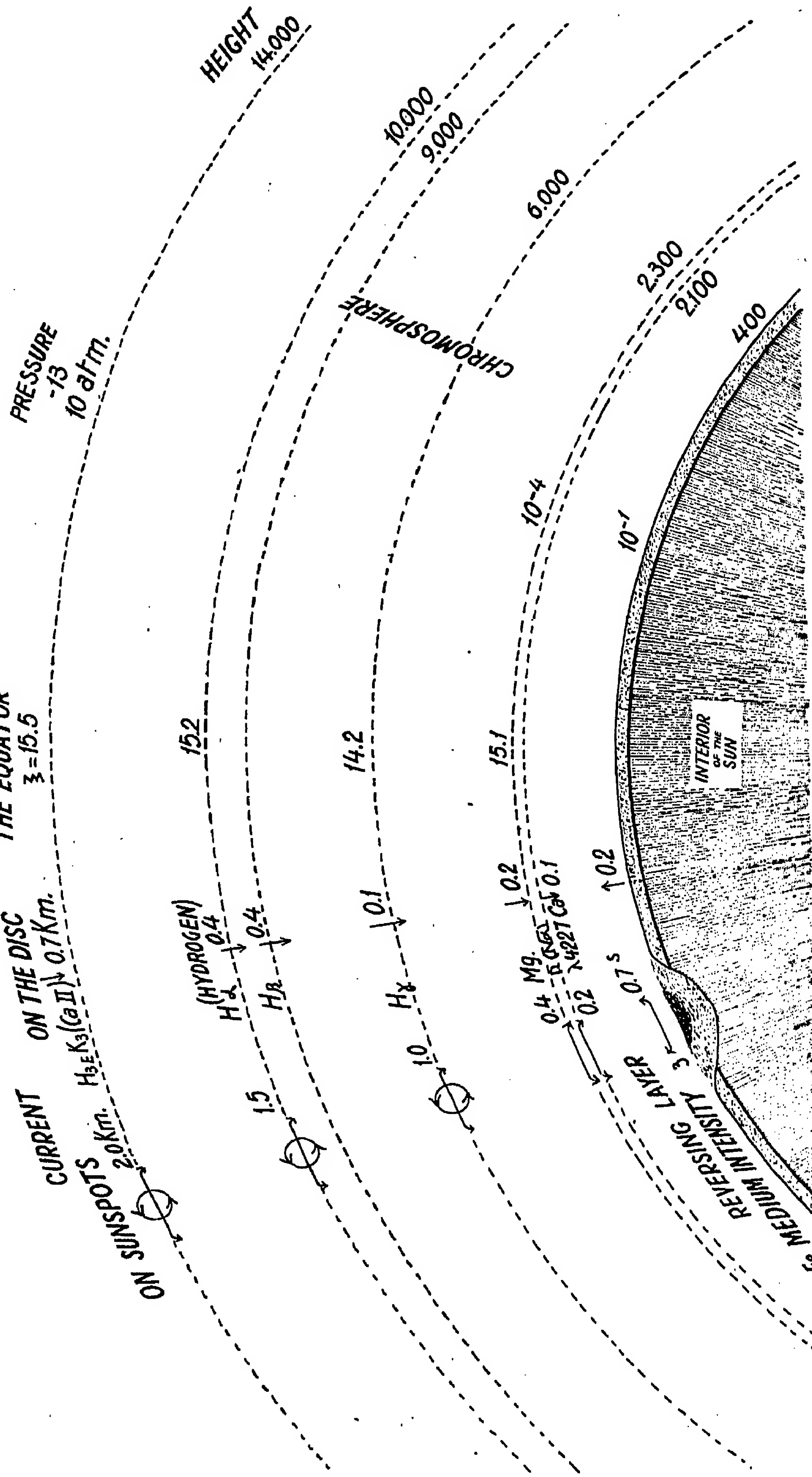

Fig. 93. Scheme of the solar atmosphere.

The figure also indicates, for each level, the pressures determined as already stated and the mean angular and linear velocities, from 0° to 45°, found for the various lines (page 166). It is evident that high velocity is associated with high level, and consequently there must exist in the upper layers a dominant and continual current from the east, diminishing in velocity the nearer it approaches the photosphere. The diagram also shows the heights, measured by means of the emission lines of the various elements in the flash spectrum during eclipses. Although the whole of this scheme will certainly be modified and developed by later observers, it must be acknowledged that these data and the theoretical considerations are in sufficiently good agreement to explain the general constitution of the solar atmosphere. In the distribution of elements and in the circulation which, from the observations described, may be conceived in the solar atmosphere, some analogy with similar terrestrial phenomena can be traced.

It is known that the percentage composition of the terrestrial atmosphere does not vary considerably in a layer of 14 km above the earth's surface, because of the mixing process produced by storms and by convection currents. Above this level the density of the heavier gases diminishes more rapidly than that of the lighter ones, so that with increasing height the lighter gases gain in percentage while diminishing in absolute density, until at 100 km the atmosphere is composed almost entirely of hydrogen with traces of helium and some other gas.

Conditions in the regions of the solar atmosphere that are accessible for spectroscopic observation seem to be very similar to those of the terrestrial atmosphere, the lighter elements gaining in percentage over the heavier elements at high levels. In the terrestrial atmosphere, below three kilometres, there is a layer in continual disturbance, with powerful convection currents and irregular temperature gradients. Above this layer and below 10 km there is a region of more stable conditions and comparatively uniform variations, although during storms it may be the seat of vertical convection currents. Finally, in the outermost layer, which is relatively calm, there is a region of uniform or reversed temperature gradient that mingles somewhat with the levels underneath.

In the lowest layer of the solar atmosphere, viz. in the region comprising the lowest levels of the reversing layer, and especially in the gases underneath, very pronounced disturbances take place; in this region is generally situated the highest part of sunspot vortices and it is here, too, that the efflux of material from the interior of the sun takes place. Above this region, which is in a state of continual disturbance, the reversing layer is in a state of relative tranquillity but more or less involved with the disturbances underneath.

The chromosphere seems to be quite distinct from this region, and the separation between the two layers seems to take place at the level of zero tangential velocity, i.e. at the level of velocity reversal, in the case of radial flux, with respect to the axis of the solar vortex.

In the case of terrestrial cyclones little is known from direct observation of the atmospheric movements above the centre of the storm, whereas in the case of storms in the solar atmosphere the point of observation is outside and hence the movements of the highest levels are visible.

Although the general circulation of the two atmospheres must necessarily be very different, it seems probable that cyclonic storms, whatever their determining causes may be, follow the same hydrodynamic laws, and that the observations in two bodies as different as the sun and the earth may supplement each other in explaining their various phenomena.

Reverting to the displacements of Fraunhofer lines in the photosphere as evidenced by direct comparison between their wavelength and those obtained from the same elements in the laboratory, it must be added that the wavelengths of the lines observed at the centre of the sun's disc do not coincide with those observed at the limb.

Halm, who in 1907 discovered and measured these displacements at the limb with respect to the centre, finding them to be of the order of 0·01 A towards the red, then ascribed their cause to an actual pressure in the reversing layer, which was greater at the limb than at the centre; as a matter of fact, the lower layers are subject to a greater pressure because of the relatively longer path traversed by light coming from the limb as compared with light coming from the centre. Buisson and Fabry, by a similar comparison of the spectrum at the

centre, come to the conclusion that the displacements are due to the broadening of the lines at their red edges, whereas the violet edges retain their normal positions. Later researches by Adams, extended to a large number of lines from the violet to the red, confirm the previous results, as may be seen in the following table, giving the displacements for groups of different wavelengths and intensities.

In view of recent determinations of pressure in the solar atmosphere, to which we have referred, it is no longer possible to suppose that the limb effect is due to this cause, as Halm

LIMB—CENTRE DISPLACEMENTS IN ANGSTROM UNITS
(ADAMS)

Region	*Intensities* 1	2–3	4–6	*Most intense lines*
4300A	+ 0·004	+ 0·005	+ 0·006	very small, practically zero
4800A	5	6	8	
5300A	6	7	9	
5800A	7	8	9	
6300A	9	9	10	

believed, and it is necessary to think of other causes such as the effect due to the gravitational field, the Doppler effect, as a consequence of convective motions in the solar atmosphere, and other possible effects.

It is known that, as a consequence of the relativity theory, the wavelength of a given radiation must increase and therefore shift further towards the red the greater the gravitation potential at the surface of the heavenly body from which it is emitted. This displacement, foreseen by Einstein's theory and constituting as it were an experimental proof of that theory, produces at the sun's surface the same result as would be produced by a Doppler effect due to a velocity of 0·635 km/sec. This corresponds, for a radiation of a wavelength 4000 A, to a displacement $\Delta\lambda$ equal to 0·008 A towards the red. This shift should be proportional to the wavelength and conse-

quently not separable from an actual Doppler effect, due for instance to convective movements; but since these movements, as we have seen, depend on the intensity of the lines, whereas the Einstein effect is independent of the intensities, it should be possible to separate them by comparing the wavelengths measured in vacuo with those measured at the sun's centre and limb.

From determinations carried out on a large number of lines, with the powerful instrumental resources of Mount Wilson, St. John rightly concludes that the displacements of the Fraunhofer lines are for the most part due to a combination of the Einstein effect and the Doppler effect as a result of convective movements, which we may call the "St. John effect." As a matter of fact, lines which originate at a mean level of about 500 km above the photosphere produce displacements at the centre of the sun in accordance with those to be anticipated on account of general relativity. Below this level, viz. in the region where 99 per cent of the sun's rays originate, there must be ascending currents that increase the intensity the deeper we penetrate into the photosphere. The iron lines, belonging to the lowest level, give an upward velocity of about 0·2 km/sec.

The St. John effect vanishes at the solar limb, because the movement of the vapours then becomes perpendicular to the line of sight, and the difference: λ limb minus λ vacuum arc corresponds almost exactly to the Einstein effect. When considering the iron lines of high, medium and low level, the mean residue: λ limb minus λ vacuum arc differs by $+$ 0·0015 A from the theoretical prediction for the Einstein effect.

This difference would be a residual effect at the limb, due perhaps to anomalous dispersion or to differential diffusion, because other possible effects such as the "Zeeman effect," due to the general magnetic field of the sun (page 220), are too feeble, and the "Stark effect" has up to the present never been detected on the sun. As to anomalous dispersion, the low pressure existing in the reversing layer renders it improbable that this could have a noticeable effect on the wavelength at the limb. On the other hand, molecular diffusion might, according to the Raleigh–Schuster theory, account for this residual shift at the limb. As a matter of fact the coefficient of

diffusion varies with the square of the refracting power, and since the resulting refraction is a little greater at the red edge than that at the violet edge of a line, this would give a differential effect tending to broaden the lines at the red edge.

The relatively short trajectory in the layers of low density at the centre of the disc explains the absence of a differential broadening at the centre, whereas the much longer trajectory through the lower layers would produce at the limb the conditions favourable to the differential effect.

The conclusion of what has been said up to now is, at the present stage of research, that the most important causes responsible for the difference between solar and terrestrial wavelength are threefold and that it is possible to separate their effects. These are due: (*a*) to the influence of the sun's gravitational field on the motion of the atoms, which is foreseen by the theory of general relativity (Einstein effect); (*b*) to convection currents at the observed levels of the solar atmosphere (St. John effect), which seems to be corroborated also by the fact that in the atmosphere of the stars there is an analogous effect, more pronounced as the temperature of the stars increases; (*c*) to differential diffusion, which has its maximum effect in the longest paths traversed by the light from the sun's limb (limb effect).

The Einstein effect is active in all parts of the solar disc; the St. John effect, in a downward direction at high levels and in an upward direction at the lower levels, is a maximum at the centre of the disc and ceases at the limb; the effect at the limb, if real, must probably be ascribed to the causes stated above and must be a function of the intensity of the lines and hence of the spectroscopic level of observation.

However, the problem of these shifts is not yet solved definitively. It is necessary to cite further the researches and conclusions arrived at by Burns and Meggers, who carried out extensive measurements of fundamental wavelengths on the sun and comparisons between these wavelengths and those obtained with the arc in vacuo. These investigators, confirming the increase of the shift towards the red with increasing intensity of the lines, note that a line of asymmetrical absorption shifts indefinitely with increasing absorption, and hence, in order to explain the shift towards the red, it would merely be necessary

to assume that all the sun's rays are slightly asymmetrical with an asymmetry that increases somewhat according to the wavelength. The height above the photosphere at which the lines may be observed in the flash spectrum is in the first place related to the intensity of the line, and the level directly determined in this way is thus always dependent on the intensity itself.

The red-shift may consequently be considered to be associated with intensity rather than with level. According to the above observers it is necessary, before it will be possible to determine the existence of the gravitational shift, to find the value of another and slightly greater shift, which shows itself as a displacement increasing with increasing intensity of the line. Up to the present only the differential effect of this shift is measurable, i.e. the increase of shift of the intense lines compared with that of the faint lines.

Magnetic Fields and Magnetic Classification of Sunspots. The Law of Sunspot Polarity

The existence of a vortex motion of the gases on the sun's surface in the regions above the spots has been established, as already stated, by spectroheliograms taken in light of the $H\alpha$ line. The appearance of the simpler vortices around the spots generally indicates a rotation analogous in direction to that which obtains on the earth, namely, left-handed in the northern hemisphere and right-handed in the southern hemisphere.

The direction of the vortices which are formed in the terrestrial atmosphere is obviously determined by the increase of linear velocity of the air from the poles to the equator as a result of the earth's rotation. The rules governing "solar cyclones" must be more complicated, as is also evident from the fact that the directional sense is not so general, there being examples of adjacent spots in the same hemisphere with vortices rotating in opposite directions.

Sometimes the dark flocculi of hydrogen, viz. the filaments, are attracted by the nucleus of the spots and disappear in it, at a velocity that may attain 100 km/sec. But this is not a general case, and here the spectrohelioscope is a better aid

than the spectroheliograph for following the progress of the phenomena.

Hale finds that, when a flocculus is devoured by the neighbouring spot, it ends with a dark head, usually of almost circular form, and is sometimes accompanied (in the position of the slit which gives the maximum of intensity) by a short tail. In many cases this head falls exactly upon the outer extremity of the penumbra of the spots, which is clearly visible when the second slit is placed beyond the wings of $H\alpha$. This head, the advance of the maximum intensity and the high velocity of descent, are the essential characteristics of these phenomena.

The presence of a vortex movement in solar regions where there are spots, is nearly always visible in the all-round distribution of hydrogen flocculi; it was this fact that suggested to Hale, in 1908, the hypothesis that a sunspot is the centre of a vortex in which the electrified particles produced by ionization in the solar atmosphere are caused to rotate at a considerable velocity. If we may suppose that a preponderance of positive or negative ions exists in the gases rotating at the spot, it necessarily follows that there is a "magnetic field" directed along or round the axis of the vortex.

It has actually been ascertained by the Evershed effect that metallic vapours have a predominantly radial instead of a vortex movement, but this may depend on the spectroscopic level at which observation has to be effected, so that we cannot detect the influx and efflux of the vapours in the direction of the axis of the vortex. Nevertheless, the hypothesis propounded by Hale, viz. that sunspots are the seat of magnetic fields of sufficient intensity to be evidenced by the Zeeman effect, was immediately confirmed by observations obtained by him in a suitable manner.

It is known that if a "normal Zeeman triplet" is observed along the lines of force of a magnetic field, the central component p is not visible, and the two lateral components n are circularly polarized in opposite directions. If we mount over the slit of the spectroscope a "quarter-wave plate" and a "Nicol prism," then either of the n components may be extinguished at will. Having extinguished one of the components, we shall see this component appear for a given position of the

Nicol; when the current in the magnetic field is reversed, the other component will be extinguished. We thus have a simple method of determining the "polarity" of the magnetic field, which may be used until the angle between the line of sight and the lines of force does not exceed sixty or seventy degrees. In this case, however, the component *p* of the triplet is also visible, and the elliptically polarized light of the components *n* can only be partially extinguished.

We will consider a spot at the centre of the sun's disc and suppose that it is the seat of a vortex, with its axis directed along the line of sight. In this case, if a powerful magnetic field is produced by the vortex, the spectral lines due to the vapours on the spot will be separated into doublets, with the components circularly polarized in opposite directions.

The phenomenon of the doubling of the lines was already noted in 1870 by Young and subsequently studied by W. M. Mitchell, but had been ascribed to an inversion of the line, which, as we have seen, occurs for more intense lines as a result of the increased thickness and density of the vapours. With the greater dispersion given by the spectrographs fitted to the solar towers, Hale succeeded in observing the separation of the components, and showed that it was not due to a double reversal but to the Zeeman effect, as he had succeeded in proving by the Nicol and by the quarter-wave plate that the two components are polarized circularly and that the polarity is reversed when the direction of the vortex is reversed, as happens in opposite hemispheres of the sun.

When the normal Zeeman triplet is observed perpendicularly to the lines of force, the component *p* is rectilinearly polarized with the direction of the vibrations parallel to the field, while the vibrations of components *n* take place in a plane perpendicular to the field. Hence, when a spot is brought by solar rotation near to the limb, it should be found that the lines generally become separated, showing the elliptically polarized lateral components until, when the axis of the vortex is positioned perpendicularly, the "transverse Zeeman effect" should be observed with the normal triplet.

Laboratory experiments show that under the Zeeman effect the various lines split in a different manner, so that, while some of them show the normal triplet, others separate into

quadruplets or doublets in which each of the components consists of a very narrow double line. In the magnetic field of sunspots, which is very much weaker than the field that can be produced in the laboratory, the very close lines which constitute the components of a doublet cannot be seen separately; moreover, for accurate comparison with the conditions of laboratory experiments one should know the inclination of the axis of the vortex with respect to the sun's surface.

The distance between the components of the individual doublets or triplets in a magnetic field varies considerably for the different lines. Some of them are not at all influenced by the field, others are broadened and others completely separated. For this reason it is important to compare the broadening and separation of the lines in sunspot spectra with the corresponding phenomena obtained in an artificial magnetic field. The agreement between the results of solar observations and those of the laboratory is nearly always established as shown by the following table referring to the iron doublet.

IRON DOUBLETS

λ	$\Delta\lambda$ *spark*	$\frac{\Delta\lambda \text{ spark}}{5 \cdot 1}$	$\Delta\lambda$ *spot*	δ	$\frac{\Delta\lambda \text{ spark}}{\Delta\lambda \text{ spot}}$
6213·14	0·703	0·138	0·136	− 0·002	5·2
6301·72	0·737	0·144	0·138	− 0·006	5·3
6302·71	1·230	0·241	0·252	+ 0·011	4·9
6337·05	0·895	0·175	0·172	− 0·003	5·2

The second column gives the distance between the external components of the lines observed in a magnetic field of the intensity of 15,000 gauss in the laboratory. When this $\Delta\lambda$ is divided by 5·1, we obtain in the third column numbers comparable to those of the fourth column. Hence it must be concluded that the intensity of the magnetic field on this spot was about 2900 gauss. The most intense fields observed in sunspots attain a value of nearly 5000 gauss.

Some lines, like the D line of sodium and the *b* line of magnesium (which, as we know, are at a very much higher level than the vast majority of the other lines), show a very slight separation of the components; since these lines are, on

the other hand, considerably influenced by the magnetic field, we must conclude that the intensity of the field in sunspots decreases rapidly towards the outermost layers of the solar atmosphere.

Preston's law:

$$\frac{\Delta\lambda}{\lambda^2} = \text{constant}$$

has been found to be strictly verified only for the lines of certain series. We could not, therefore, expect complete proof of this law from all solar lines, especially when lines of different elements are considered together. Nevertheless, it is interesting to determine whether the law holds good for the decrease of separation of the doublets towards the violet. It has been found that this decrease is verified for some of the iron lines, when the mean separation of a sufficient number of lines is considered. For these lines the broadening produced by the magnetic field thus decreases rapidly towards the violet.

The necessity of increasing the size of the solar image, on the one hand, in order to obtain good separation of the various elements in sunspots of a more or less complex structure, and of having large dispersion, on the other hand, in order to separate distinctly each individual component of the lines under the influence of magnetic fields, including fields of small intensity, led Hale to construct the 150-foot tower of Mount Wilson, which gives a solar image of 43 cm diameter, and its spectrograph of 23 metres focal length, which gives a linear dispersion in the spectrum of the second order of 1 A = 3 mm.

Observations, both visual and photographic, have been made daily since 1917 of the polarity and intensity of the magnetic fields on sunspots. The polarizer used for these observations consists of a Nicol composed of several sections, which covers the entire slit of the spectrograph of 130 mm length. Laid over the Nicol is a compound quarter-wave plate. This consists of so many mica strips two millimetres in breadth, one beside the other, their principal sections being normal to each other and inclined at an angle of 45° to the slit.

If, with this contrivance, one of the components of the magnetic doublet is extinguished, for example the red one,

the violet component will be extinguished in the next strip, and so on, so that the Nicol will transmit, for example, the violet component for even-number strips and the red component for odd-number strips. If the Fraunhofer lines are separated by the effect of the magnetic field they will thus present through this polarizer a denticulated appearance, the height of the teeth, i.e. the degree of separation of the components, being greater or smaller according as the field intensity is stronger or weaker; in this way the components *n*, red or violet, will be seen alternately through the adjacent strips of mica.

If the sign of the current produced by the magnetic field is reversed, the components *n* will be seen to exchange, and thus we have a simple means of determining the polarity of a magnetic field, even if that field is complex and variable in comparatively small solar regions.

For studying the phenomena of plane polarization we substitute for the compound quarter-wave plate a half-wave plate, also compound, or, for special researches, circular half- or quarter-wave plates whose position angle is adjustable.

Visual observations of the magnetic field on sunspots are carried out at Mount Wilson in the following manner: It is observed which of the two components, the violet or the red, is transmitted by a certain strip of the quarter-wave plate, and thus the polarity of the field at this point is established. Then the intensity is measured by means of a micrometer made of a small plate with plane parallel faces. By suitably inclining this plate it is possible to bring into coincidence the various sections of the adjacent spectral lines, shifted by the effect of the magnetic field. Calibrating this micrometer by measurement of the lines whose separation for a given field intensity has been determined in the laboratory, the angle to which the small plate is turned is converted into gauss. One generally observes the well-defined triplet 6173 A of iron, for which the *n* components may still be distinguished separated by a field of 1000 gauss.

Since, in general, the direction of the line of sight does not coincide with the direction of the lines of force, the circular vibrations enter the analyser as elliptically polarized light possessing also part of the linear vibrations of the mean component. Hence one has to ascertain the action of the quarter-

wave plate and the Nicol on this tangle of elliptically and plane polarized light, and deduce the relative intensity of the components.

If γ is the angle between the direction of the line of sight and that of the lines of force, assuming the sum of the inten-

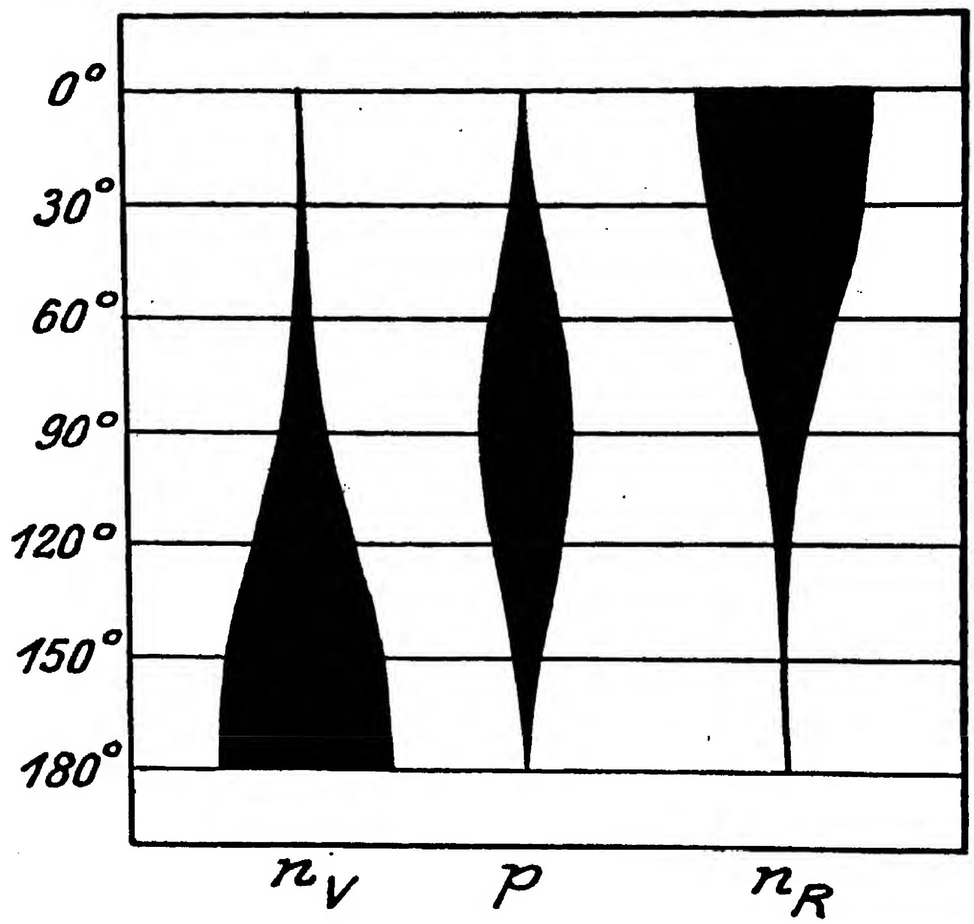

FIG. 94. Relative intensity of the three components of a normal Zeeman triplet for inclinations from 0° to 180° between the line of sight and the lines of force, observed with a Nicol and a quarter-wave plate.

sities of the components n_v violet, n_r red and p central to be equal to unity:

$$n_v + p + n_r = 1,$$

Seares finds that their relative intensities in each mica strip forming part of the quarter-wave compound plate are given by:

$$n_v = \tfrac{1}{4}(1 - \cos\gamma)^2; \quad p = \tfrac{1}{2}\sin^2\gamma; \quad n_r = \tfrac{1}{4}(1 + \cos\gamma)^2$$

The intensity variation in the three components with varying angle γ is shown in Fig. 94.

It is interesting to compare the laboratory results obtained

with the emission lines of varying angle γ with those observed in the Fraunhofer lines on sunspots.

When we are concerned with a normal triplet, the intensity trend for the lines obtained in the laboratory naturally follows that obtained from the above formulae, giving different values to angle γ. In the sun, if the spot is near the centre and is observed with the Nicol and the quarter-wave compound plate, unless the axis of the vortex is very greatly inclined to the sun's surface, γ must be almost equal to zero and thus

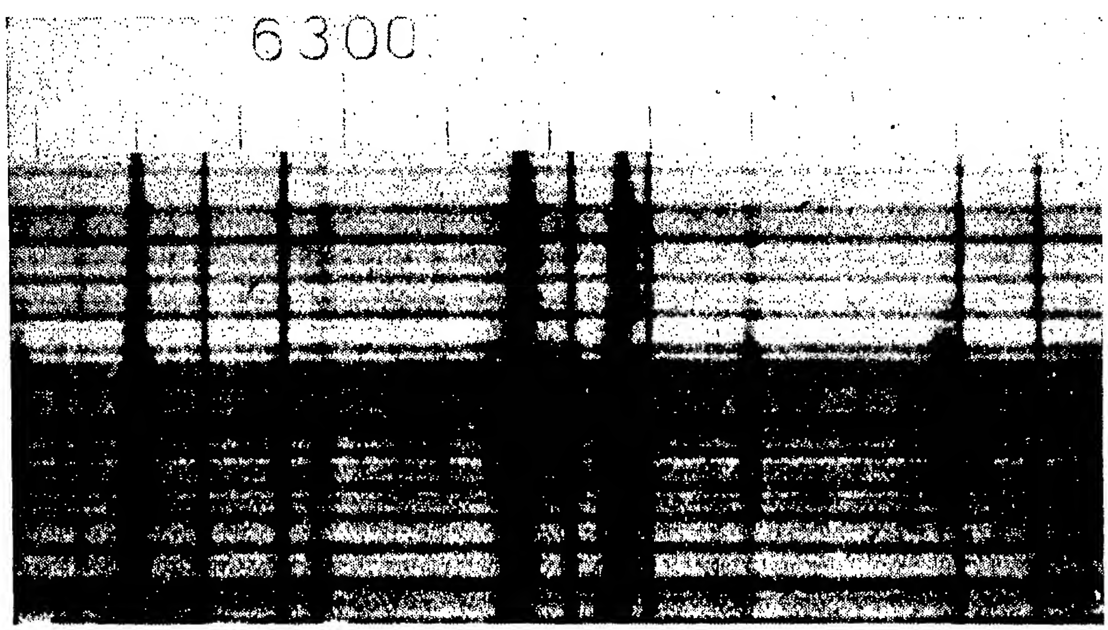

FIG. 95. Triplet of iron, 6302·7 A, in the spectrum of a spot observed near the centre of the sun with the Nicol and the compound quarter-wave plate.

The triplet shows the circular polarization parallel to the lines of force.

we see in the alternate strips the components n_v and n_r of the *Fe* triplet 6302·7 A (Fig. 95) and, faintly, the component p, owing to the inclination of the axis of the vortex to the direction of the line of sight. If the spot is near the solar limb, then observation is, as stated, carried out with the Nicol and with the compound half-wave plate.

Fig. 96 again shows the *Fe* triplet 6302·7 A, observed under these conditions. In these lines we can distinctly see p and the components n alternately. If, when the spot is near the solar limb, we assume that the lines of force at the centre of the spot are perpendicular to the sun's surface and that they gradually incline towards the borders of the umbra and over the penumbra as indicated in Fig. 97, we can ascertain

whether the phenomena of polarization vary, according to the hypothesis propounded, when the slit is directed on to the spot in the successive positions indicated from 1 to 7. If the spot is regular, we find polarities that are opposed to the opposite edges of the spot, according to the assumed inclination of the lines of force at the various points under

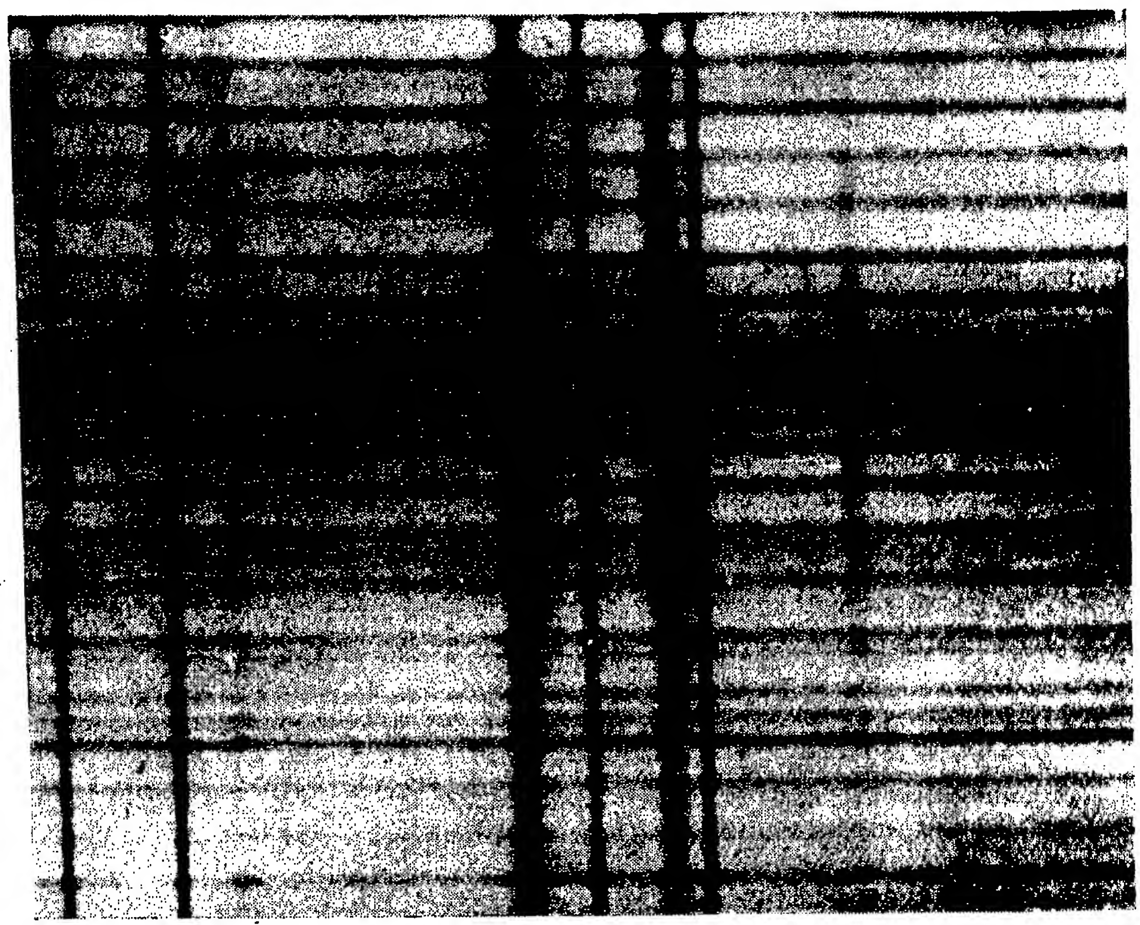

FIG. 96. Triplet of iron 6302·7 A in the spectrum of a spot observed near the solar limb with the Nicol and the compound half-wave plate.
The triplet shows the plane polarization perpendicularly to the lines of force.

examination. As a matter of fact, when the spot is observed, for example, at positions 2 or 3 (Fig. 97), the lines of force recede from the observer and n_r appears more intense than n_v. Between 3 and 4 the components n become of equal intensity, which is an indication that the line of sight is almost perpendicular to the lines of force (Fig. 96). In the successive positions of the slit the n_v component becomes more intense, which shows that the lines of force in the internal part of the spots are directed towards the observer.

Hence the real polarity of a spot, corresponding to that

resulting from observations made on the umbra when the spot is near the sun's centre, may also be determined near the limb by observing that part of the penumbra which is situated near the sun's centre.

These observations are complicated owing to the fact that the polarities of the spots are not always regular, especially in groups of complicated form; nevertheless, from observations effected by the above method and, for spots at the limb, with a Nicol and a half-wave plate mounted on a graduated circle in such a way that the angle formed by its main axis with

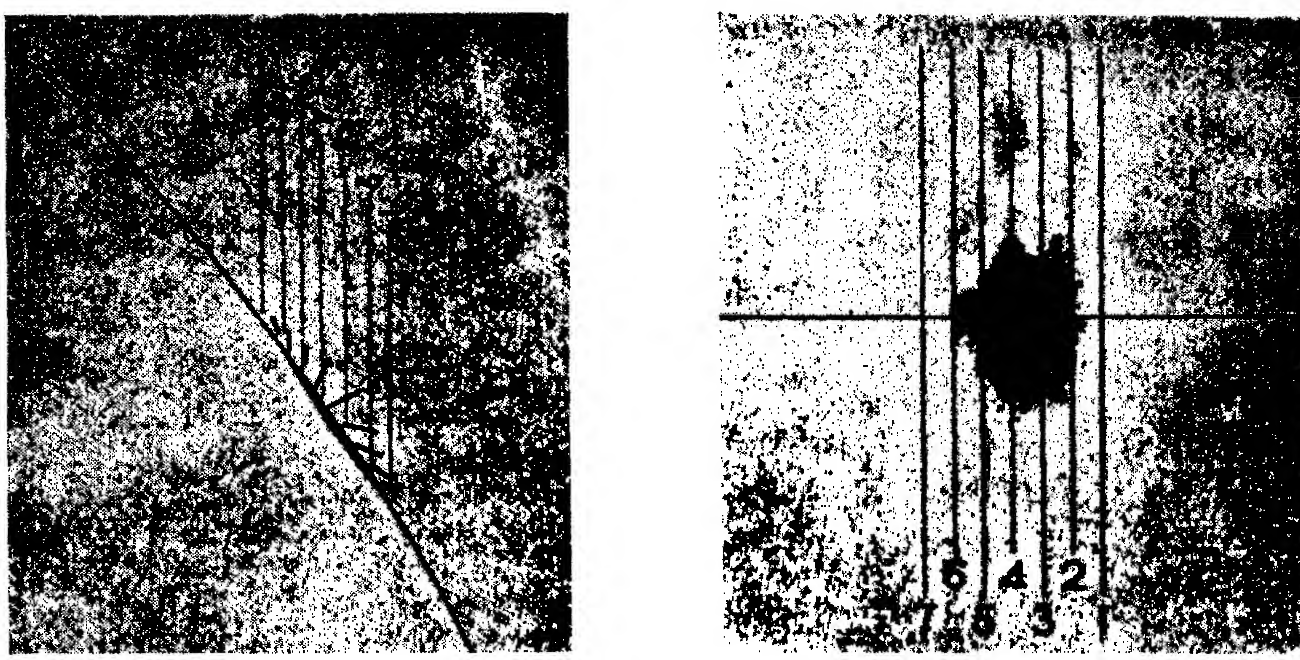

FIG. 97. Positions of the slit on a spot for examining the direction of the lines of force.

that of the Nicol can be determined, we find that at the centre of the spot the angle between the lines of force and the sun's radius is zero, and increases towards the edge to about 70° at 0·9 from the centre of the spot, the diameter of the spot being unity.

Figs. 98 and 99 represent two sections of a few angstroms of a sunspot spectrum map obtained by Ellerman at the Mount Wilson tower with the polarizer consisting of the Nicol and the compound quarter-wave plate. The spots were always observed near the central meridian in the solar cycle from 1912 to 1923, and the chart extends from 3900 A to 6600 A, showing for all the Fraunhofer lines visible in this region how they are more or less influenced by the magnetic field.

A large number of lines not influenced by this field are due to the bands which, as stated (page 97), are present in sunspot spectra. The chart also shows which lines are decomposed into normal triplets and which lines have a more complicated composition. In general the most intense lines

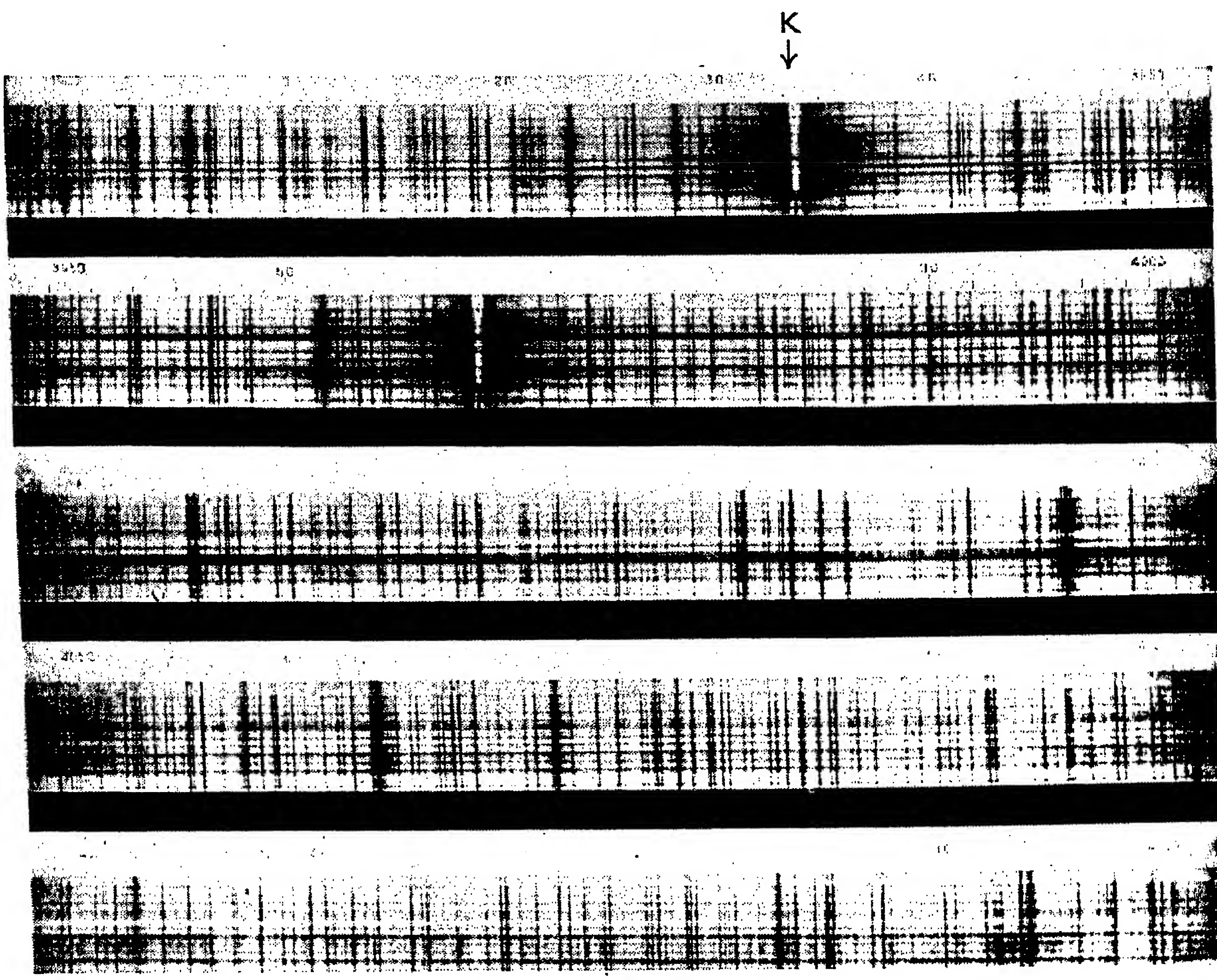

FIG. 98. Sections of sunspot spectra photographed at Mount Wilson with the Nicol and the compound quarter-wave plate, showing the Zeeman effect.

seem to be less influenced by the field, so that some of them are not entirely separated. This shows that the intensity of the magnetic field decreases the further we go above the spots; as a matter of fact the Zeeman effect is no longer observed for lines which are produced at high levels as, for instance, in the D lines of sodium or in the *b* lines of magnesium.

When discussing the characteristics of sunspot groups (page 80), we stated that they frequently consist of a pair of spots which may be several degrees apart. The leader or

preceding nucleus of such a group is often the first to be formed, but sooner or later a second nucleus comparable to the first in size, but frequently smaller or split into several components, appears behind the other. Sometimes both members of the group appear simultaneously, and in other cases the follower is formed first. Many small spots accompany the two larger ones, either grouped near them or spread over the space between

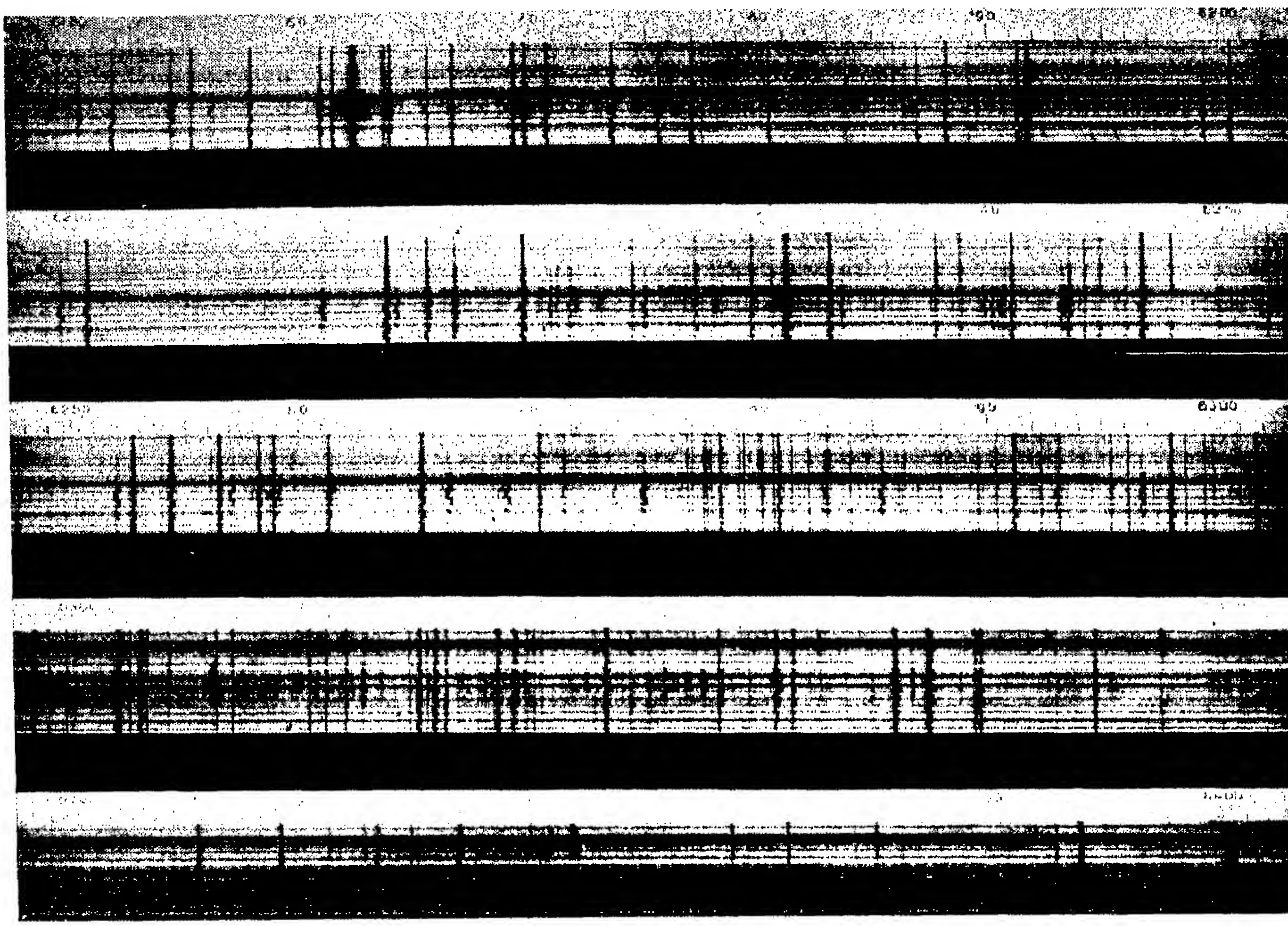

FIG. 99. Sections of sunspot spectra photographed at Mount Wilson with the Nicol and the compound quarter-wave plate, showing the Zeeman effect.

the two main nuclei. It has also been noticed that the axis of these groups is more or less inclined towards the equator. The magnetic characteristic of these binary groups is that the two principal members nearly always have opposite "polarity."

The tendency towards a bipolar structure is almost general in sunspots, for even in cases where the spots are single there are often traces of asymmetry due to the presence of faculae or flocculi following or preceding the spots. In spectroheliograms it is often found that a single spot or a group of small

spots with the same magnetic polarity are situated at the preceding extremity of a mass of calcium flocculi prolonged

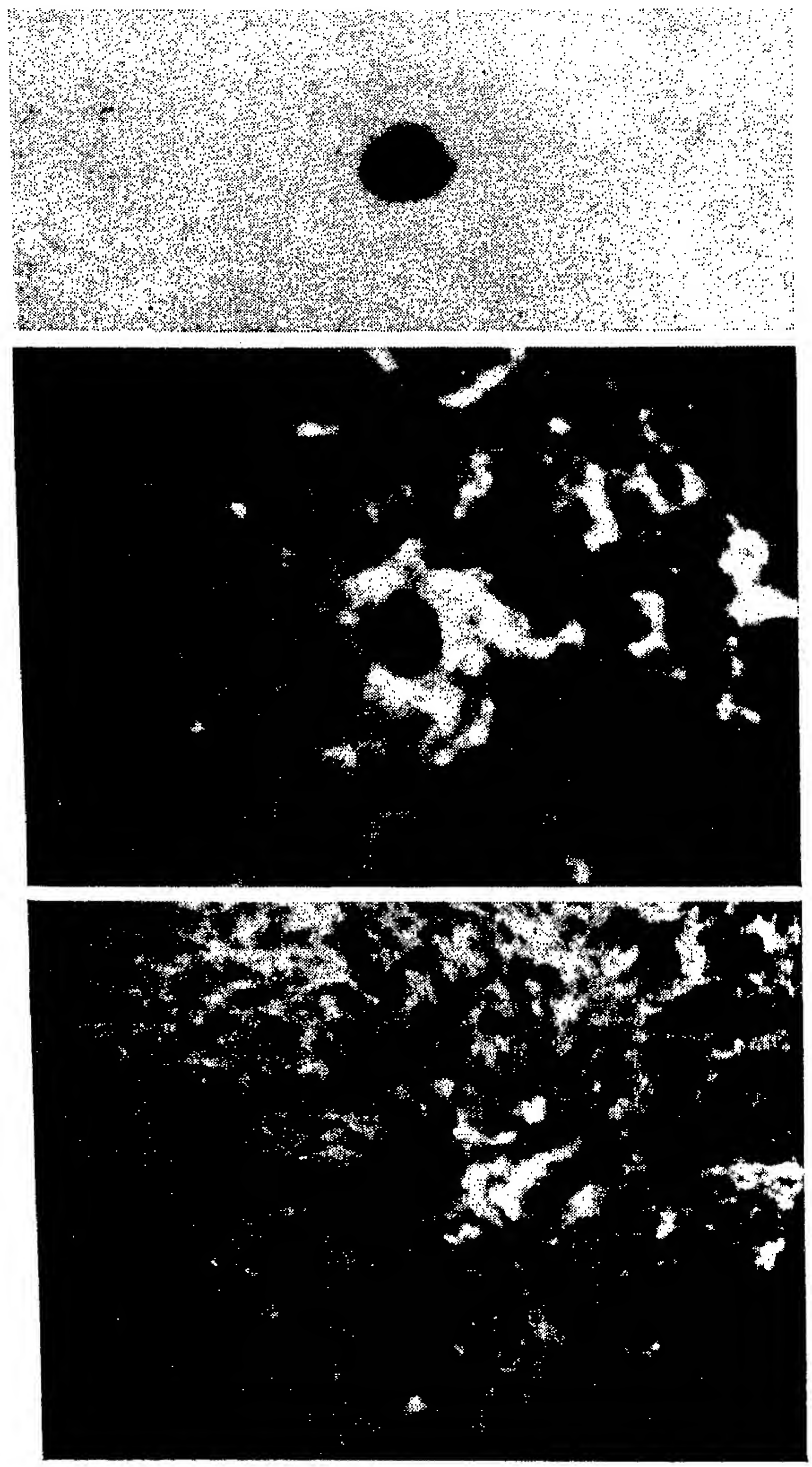

FIG. 100. Unipolar spots (α).
(Above: direct, middle: calcium; below: hydrogen images.)

in a direction that is not greatly inclined to the solar equator.

This behaviour of sunspots and flocculi, together with the

observations of the magnetic field, lead to the following "magnetic classification" adopted at Mount Wilson. This comprises

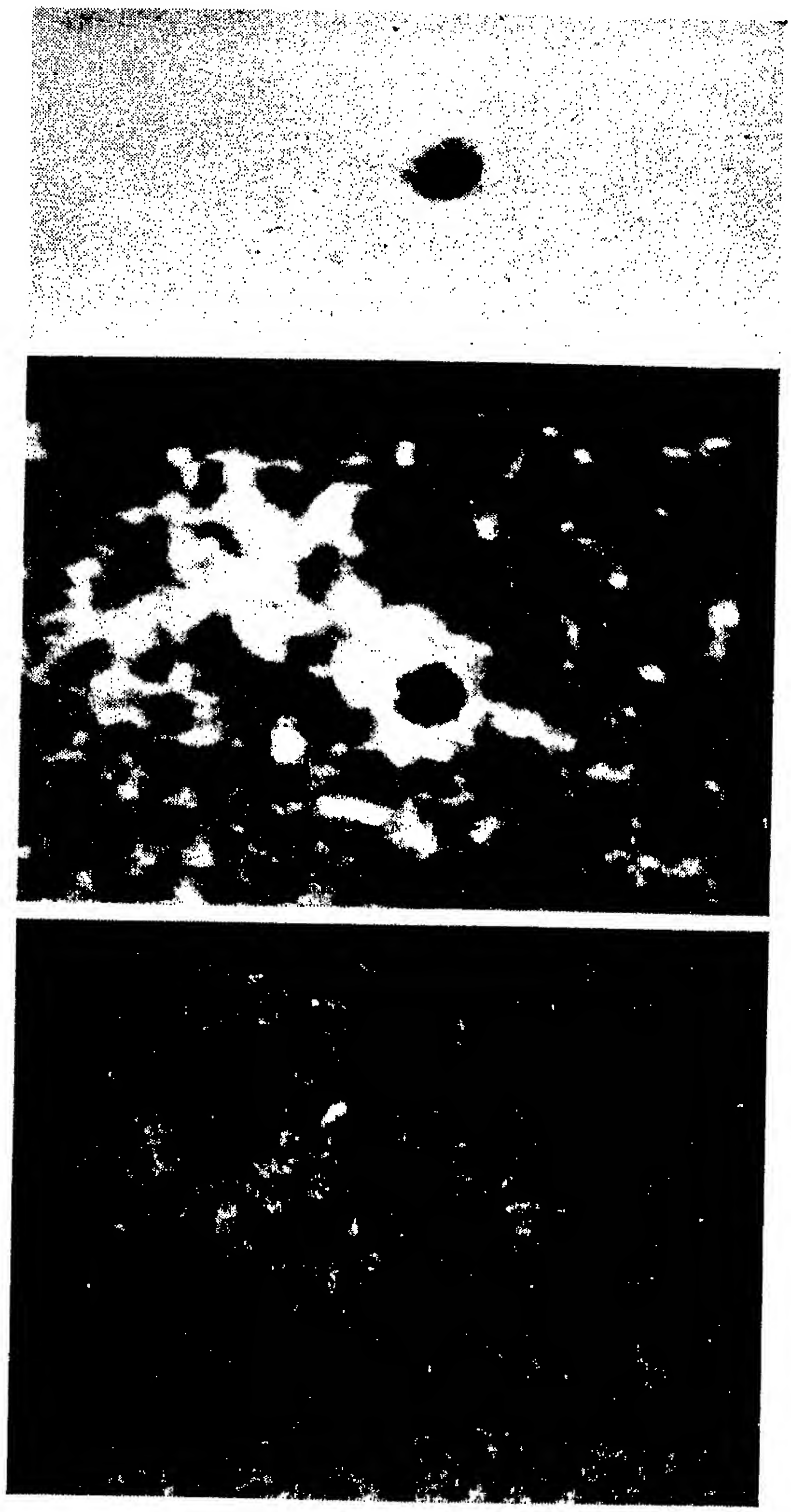

FIG. 101. Unipolar spots (αp).

three classes based chiefly on the determination of the magnetic polarities and on the distribution of flocculi accompanying sunspots.

(I) Unipolar Spots.—Single spots or groups of small spots having the same magnetic polarity. In this class the distribution of flocculi may assume different aspects, viz.

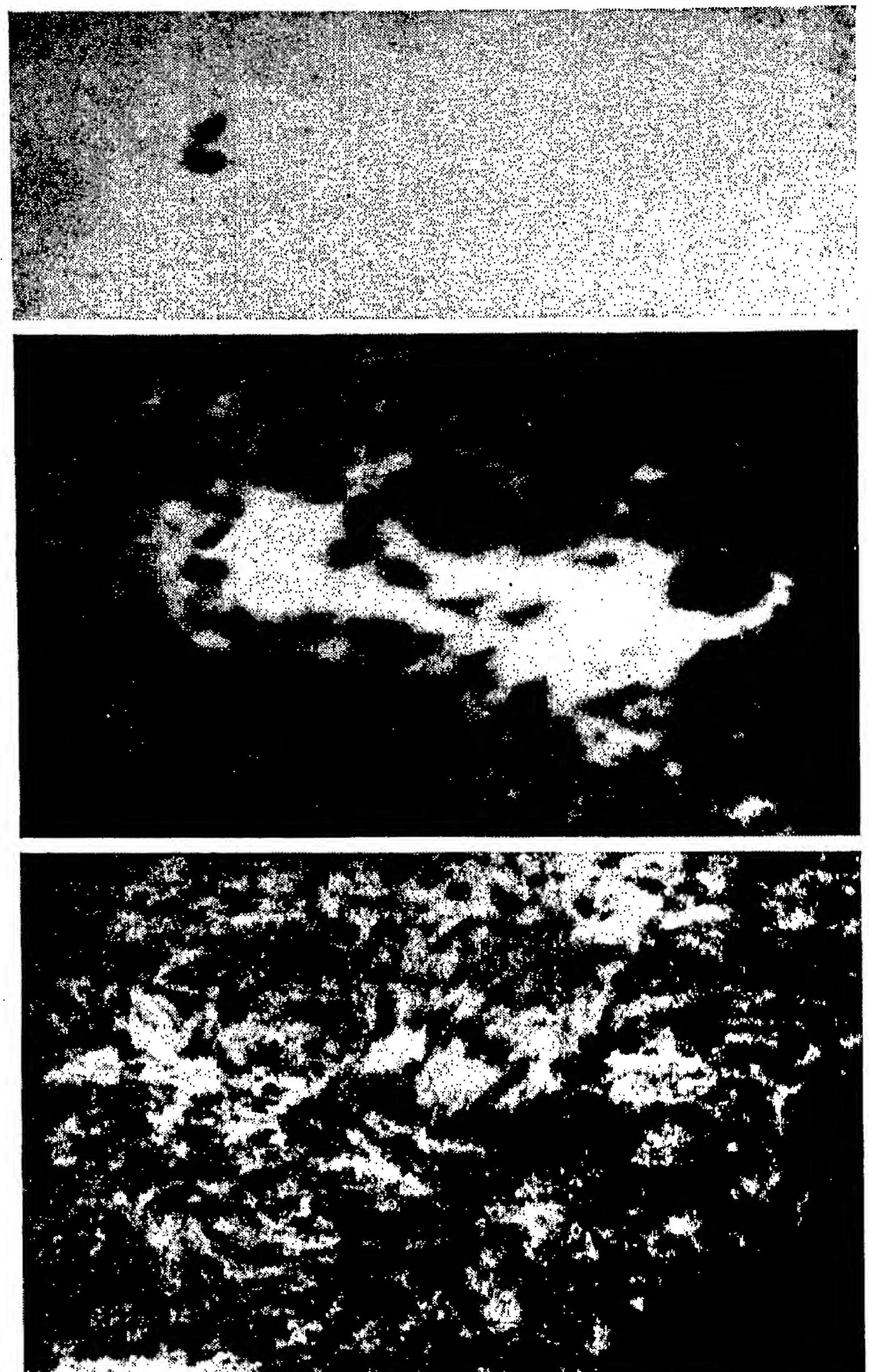

Fig. 102. Unipolar spots (αf).

(α) unipolar spots with flocculi preceding or following the centre of the group in a fairly symmetrical manner (Fig. 100);

(αp) the centre of the group precedes that of the surrounding flocculi (Fig. 101) (αf); the centre of the group follows the centre of the surrounding flocculi (Fig. 102).

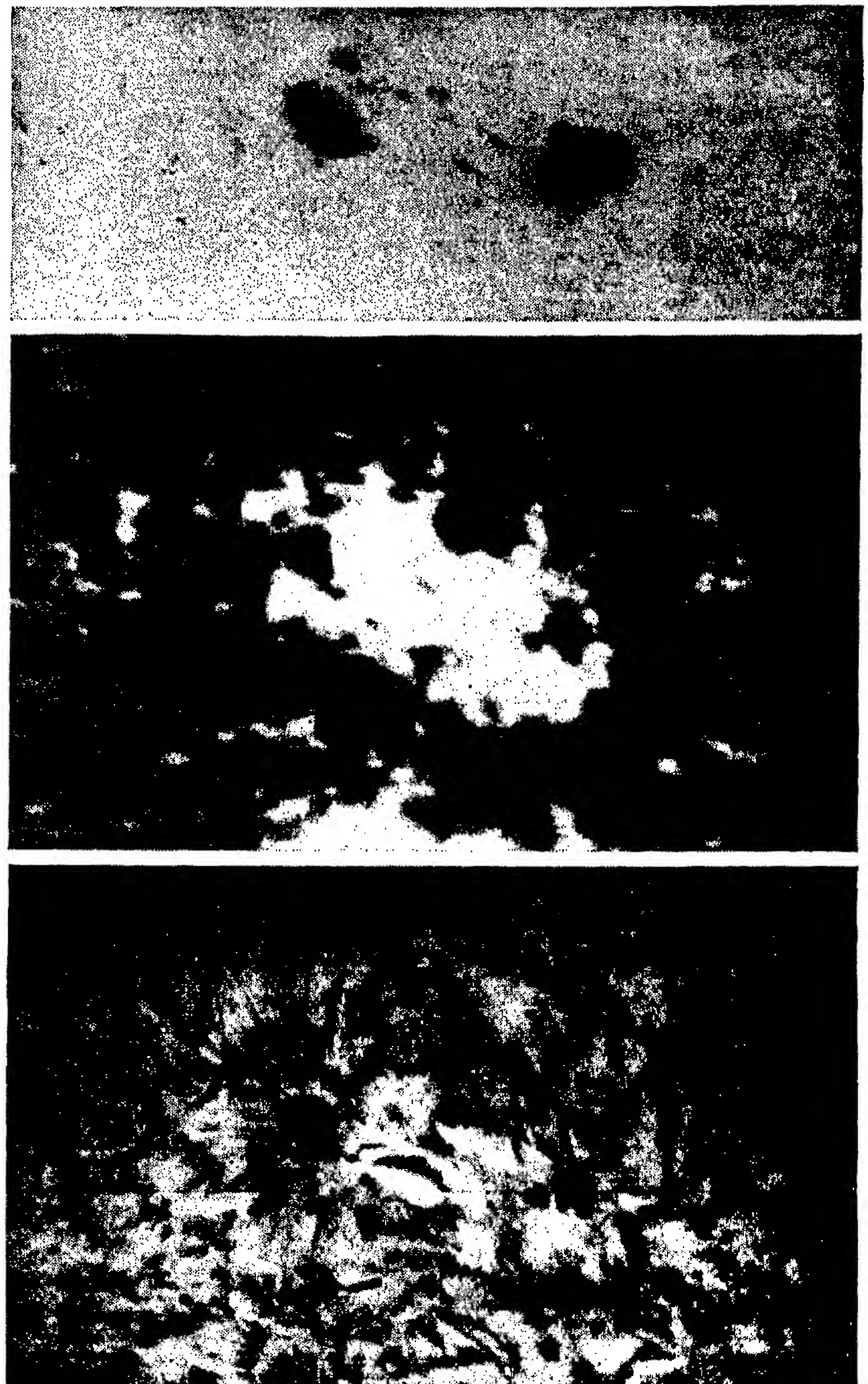

FIG. 103. Bipolar spots (β).

(II) BIPOLAR SPOTS.—The simplest and most characteristic group of bipolar spots consists of two spots of opposite polarity.

The conjunction of the two spots is generally slightly inclined towards the solar equator. Each member of the group may be

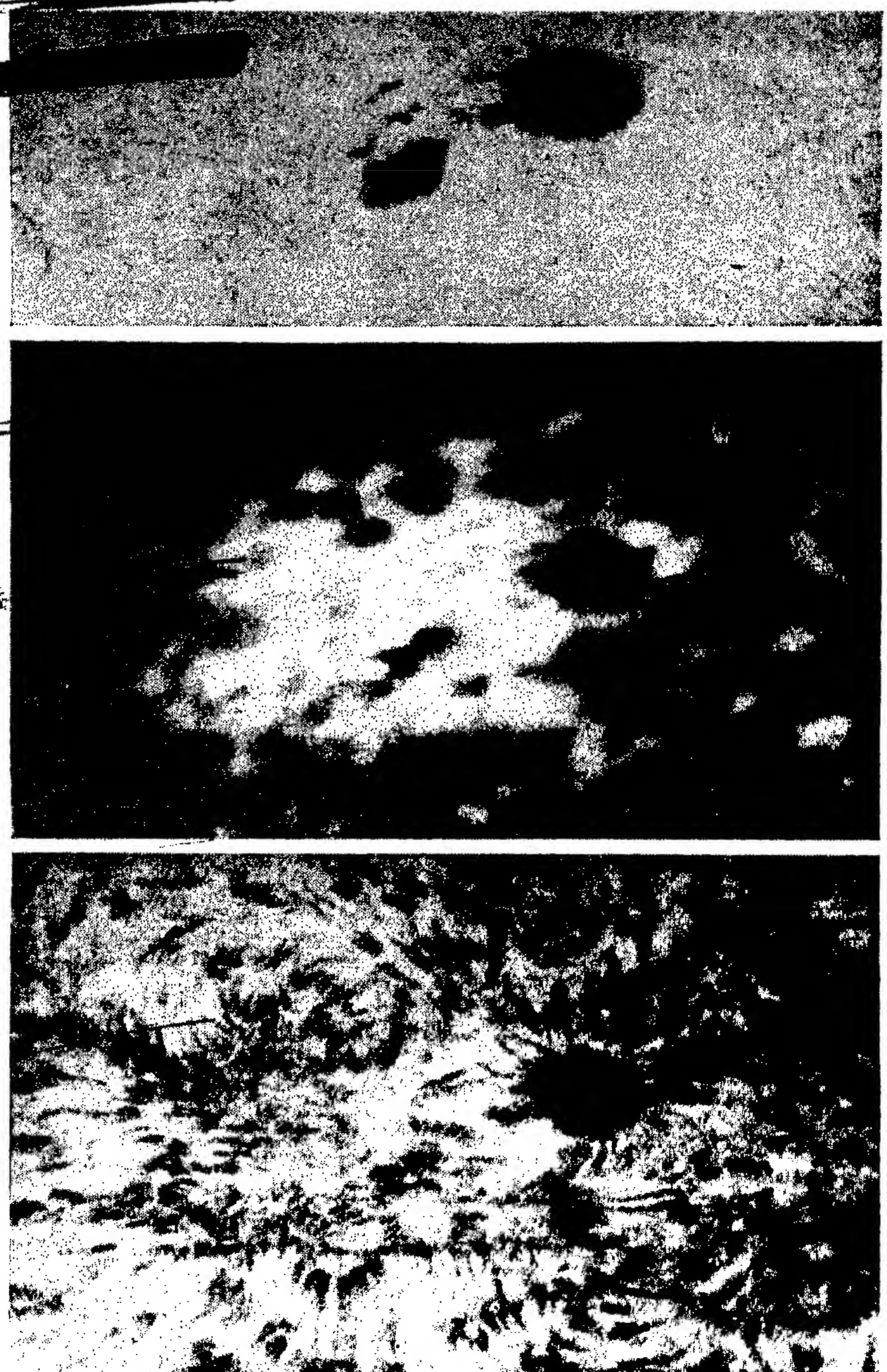

FIG. 104. Bipolar spots (βp).

accompanied or replaced by many small spots; but the vast majority of spots constituting the leading or following members are of opposite magnetic polarity. Hence this class is divided

into four sub-classes: (β) Bipolar spots in which the members, both leaders and followers, formed by one or more spots are

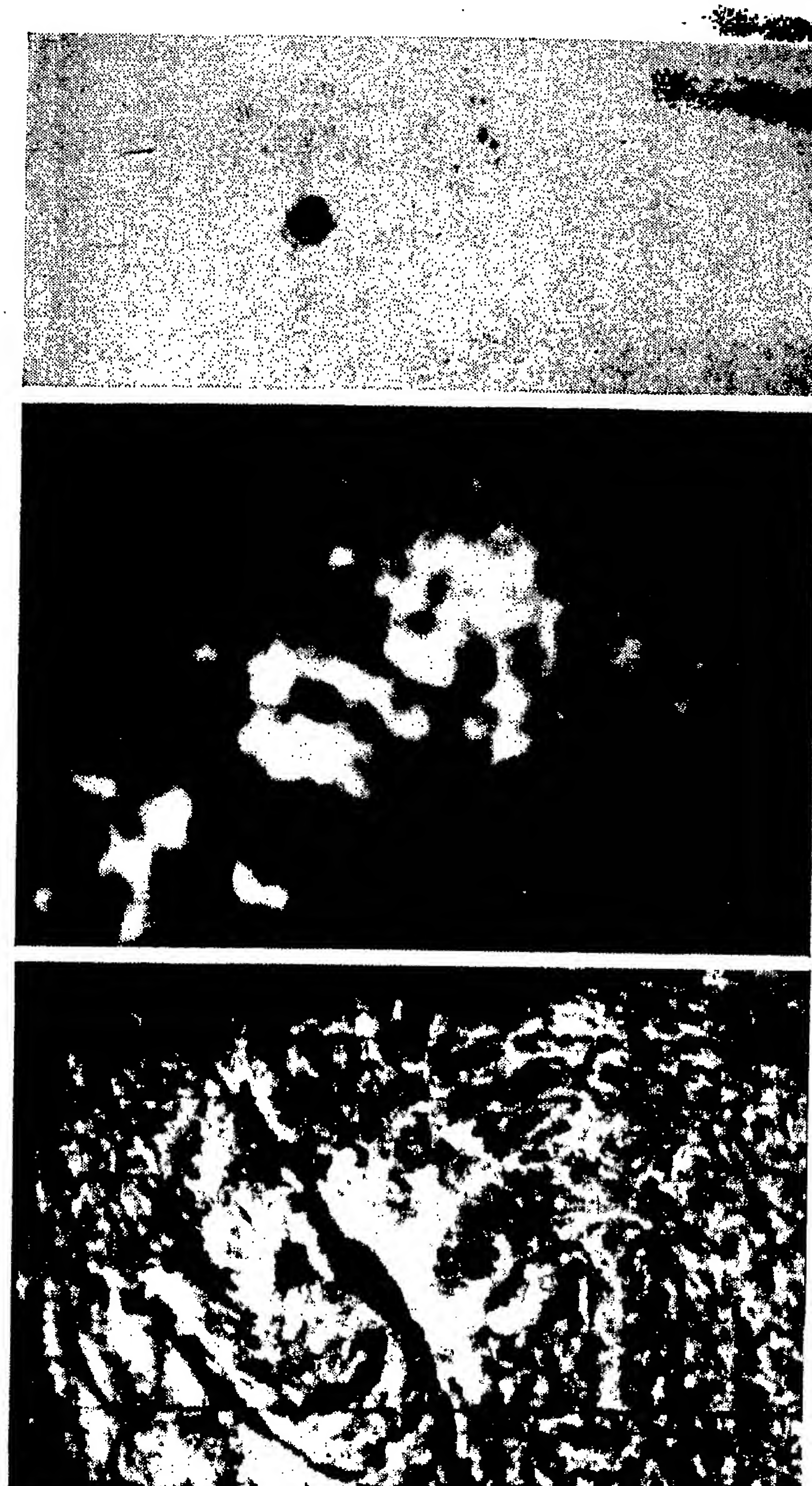

Fig. 105. Bipolar spots (βf).

approximately of equal area (Fig. 103); (βp) the leader is the principal member of the group (Fig. 104); (βf) the follower is the principal member of the group (Fig. 105); ($\beta\gamma$) the

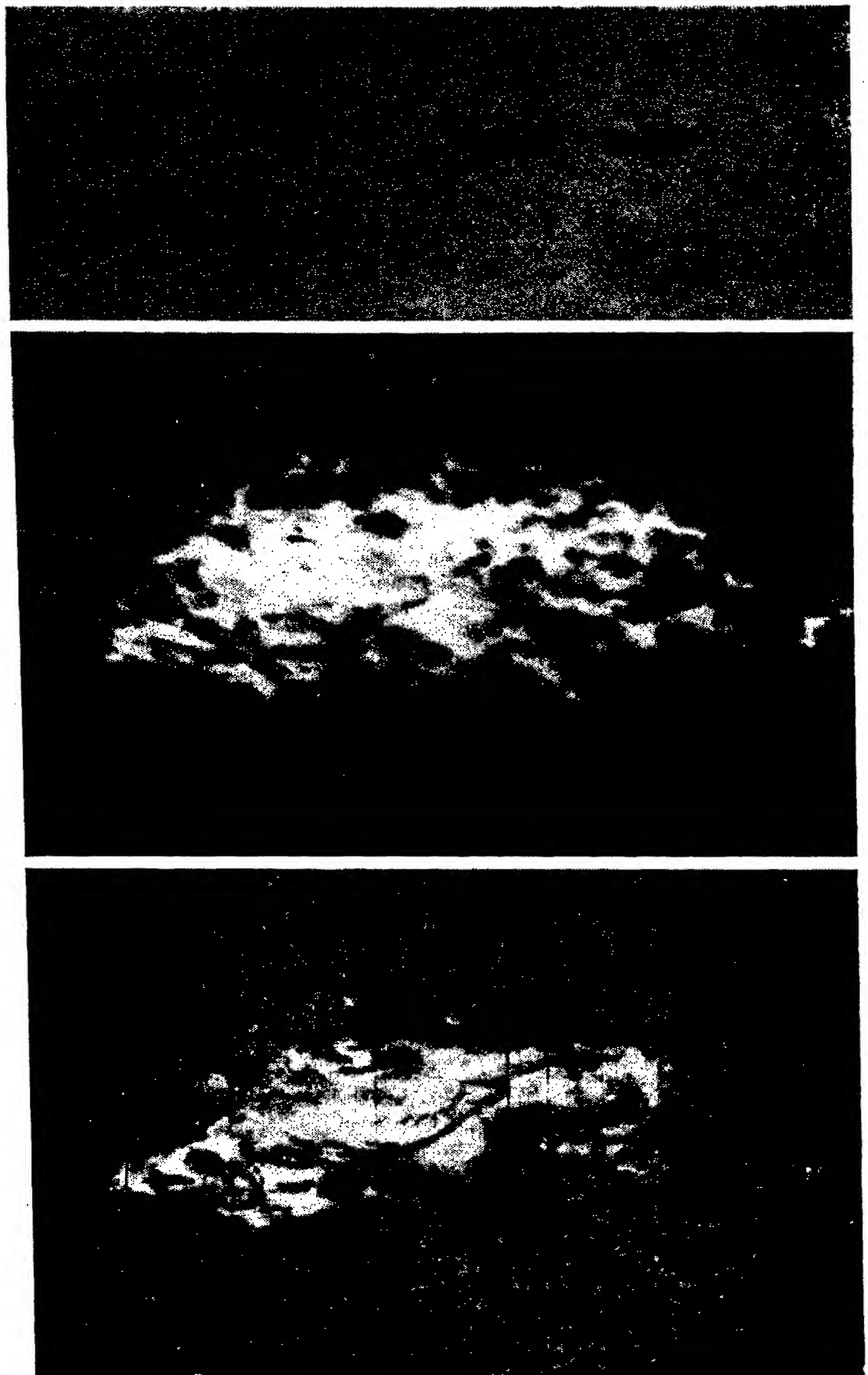

FIG. 106. Bipolar spots ($\beta\gamma$).

leader and the follower are accompanied by minor components of opposite polarity (Fig. 106).

(III) Multipolar Spots.—(γ) groups of this type, which hardly attain one per cent of the total number of sunspots observed, comprise spots of opposite polarity, irregularly distributed, which it is impossible to classify as bipolar groups (Fig. 107).

On the basis of this classification regular observations have been, and are still, carried out at Mount Wilson with the *Fe* line 6173·553 A, it being noted which of the *n* components—that towards the red (*R*) or that towards the violet (*V*)—is transmitted by a particular strip of the compound quarter-wave plate in conjunction with the Nicol. The distance between the components *R* and *V* gives the approximate intensity of the field in the observed point of the spot; this is expressed in units of a hundred gauss.

Fig. 108 shows how these magnetic observations of sunspots are carried out at Mount Wilson. In Fig. 109 the northern spot (No. 1556 of Mount Wilson), was on that day (September 13, 1919) at 2° north latitude and at 15° longitude east of the central meridian. The nucleus transmitted the red *n* component, and the intensity of the field was 3400 gauss. The other small spots (or "pores") following show opposite polarities with an intensity of 500 gauss. The southern spot (No. 1555) was at a latitude of 2° south and at 12° longitude and transmitted the violet *n* component, the field intensity being 2900 gauss. The small leading spots had a polarity opposite to the field of from 500 to 700 gauss.

The result of the magnetic classification of 2174 groups observed in the same manner from 1915 to 1924, gave the following percentage:

Classes	α	αp	αf	β	βp	βf	$\beta\gamma$	γ	*Unclassified*
Percentage	14	20	4	21	29	8	3	1	7

When searching for a law of sunspot polarity it may thus be assumed that the class of bipolar spots is that constituting the dominant type. This is also confirmed by direct observation, in so far as it has been observed that, in the case of a

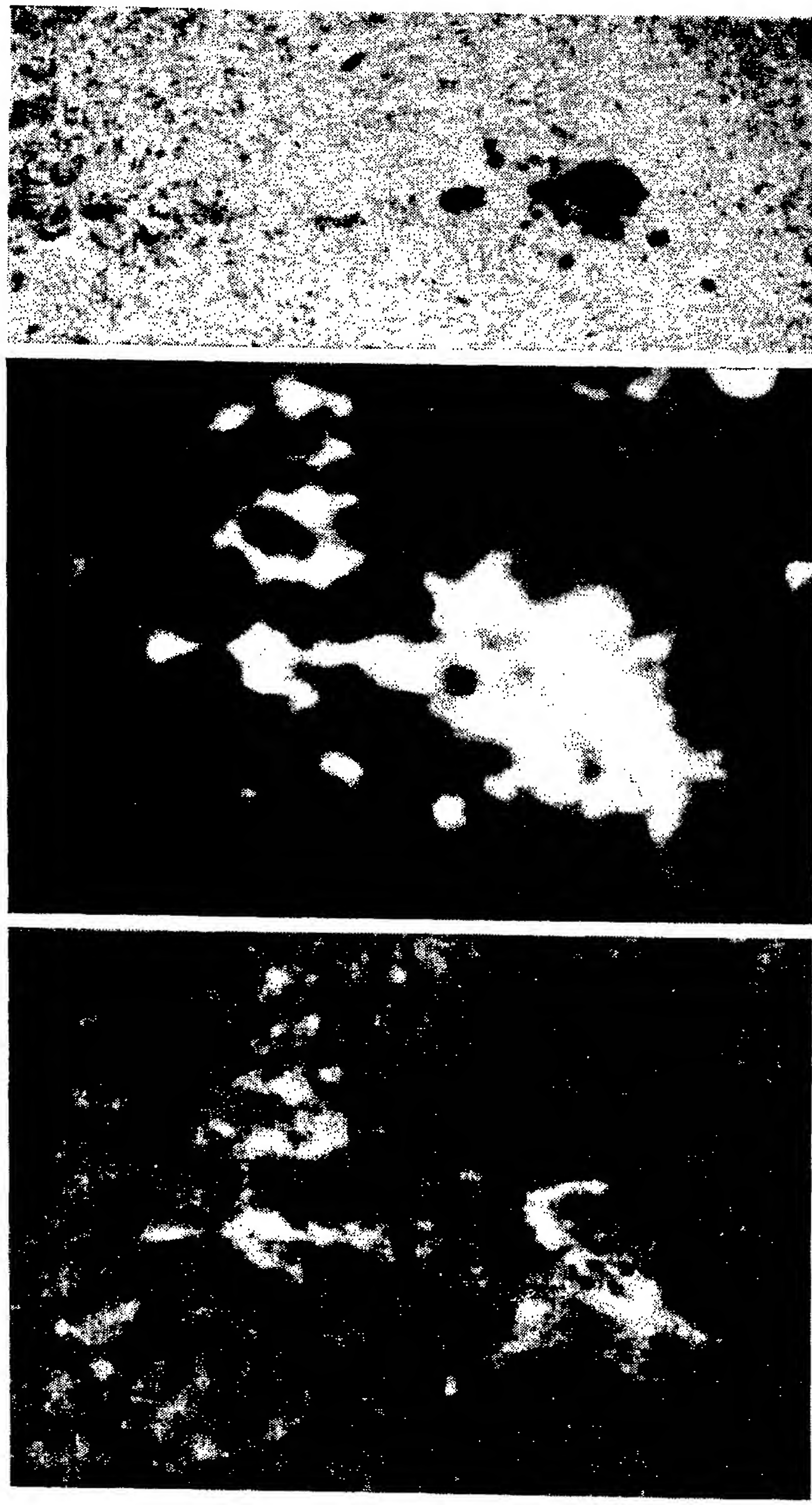

FIG. 107. Multipolar spots (γ).

well-developed single spot, this spot is very often accompanied by small spots or by leading or following flocculi.

In regular observations of polarity the Mount Wilson

astronomers found that, with the arrival of a new cycle, the polarities of the two spots in the two hemispheres altered also. Indeed, before the minimum period of 1913 the polarity of the leader spots in a bipolar group in the northern hemisphere was south or *negative*, thus corresponding to the same polarity of the magnetic north pole of the earth, while that of the follower spots was north or *positive*. The spots of the southern hemisphere showed opposite polarity, north for the preceding components and south for the following components.

As already stated, the last spots of a cycle appear at low

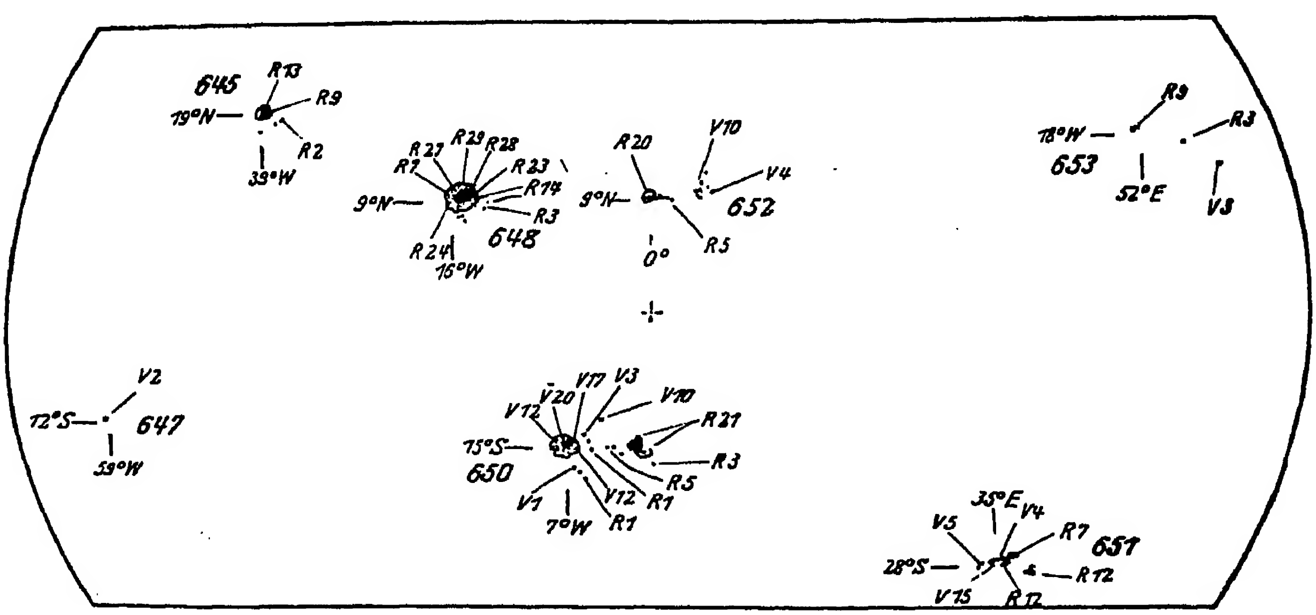

FIG. 108. Polarity of sunspots observed at Mount Wilson May 14, 1917.

latitudes, whereas the first spots of a new cycle appear at high latitudes and, as the cycle progresses, their mean latitude progressively decreases. The spots of the new cycle which began to appear in small numbers in 1912 at a high latitude, showed opposite polarity to those of low latitude of the previous cycle. During the progression of the cycle 1913–23, according as the spots became more numerous, it was ascertained that the new polarities were characteristic of all the spots observed, except only 4 per cent.

The mean latitude of the spots diminished gradually, as usually happens in each cycle, and towards their close (1922–23) they were in the vicinity of the equator. At the same time (June 1922) there appeared towards 30° latitude the first spots heralding the new cycle (1923–34). Afterwards several other

spots of the various classes, but for the most part bipolar ones, made their appearance, the vast majority of them showing reversed polarities, thus again resembling those of the cycle first observed (1901–13) after the discovery by Hale of the magnetic fields.

Also for the new cycle, which commenced at the end of 1933,

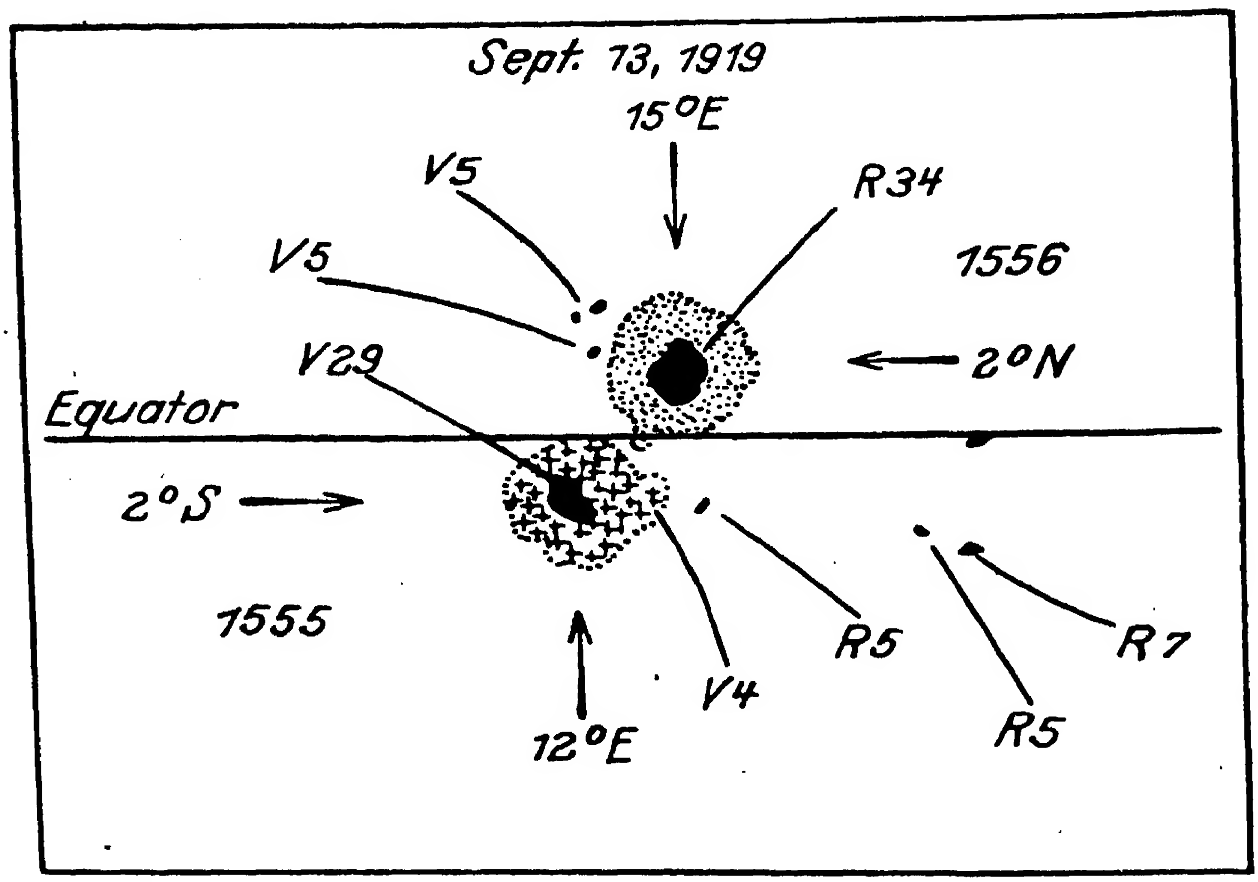

FIG. 109. Spots of opposite polarity near the solar equator (September 13, 1919, Mount Wilson).

the repetition of the phenomenon of polarity reversal has been noted and confirmed. As a matter of fact, in 1933, October 10th, a small spot was observed at Mount Wilson in latitude + 26°, with a polarity opposite to that of the other spots in the northern hemisphere. On October 28th a small bipolar group was observed in latitude — 32°, with polarities opposite to those of the other spots of the southern hemisphere. At the same time a group in latitude + 9·5° showed the polarity of the spots in the northern hemisphere of the past cycle. In this way the polarity reversal at each eleven-year cycle has now been verified during four cycles, and the important law discovered by Hale may be expressed as follows:

The sunspots of a new eleven-year cycle, which appear at high latitudes after a minimum of solar activity, are of opposite magnetic polarity in the northern and southern hemispheres. As the cycle advances, the mean latitude of the spots in each hemisphere gradually decreases, but their polarity remains unaltered. The spots of high latitude of the next eleven-year cycle, which begin to develop more than a year before the disappearance of the last spots of low latitude belonging to the previous cycle, are of opposite magnetic polarity. Hence we may conclude that, whilst the interval of about 11·5 years represents the periodical variation of the frequency or total area of sunspots, prominences and flocculi, the

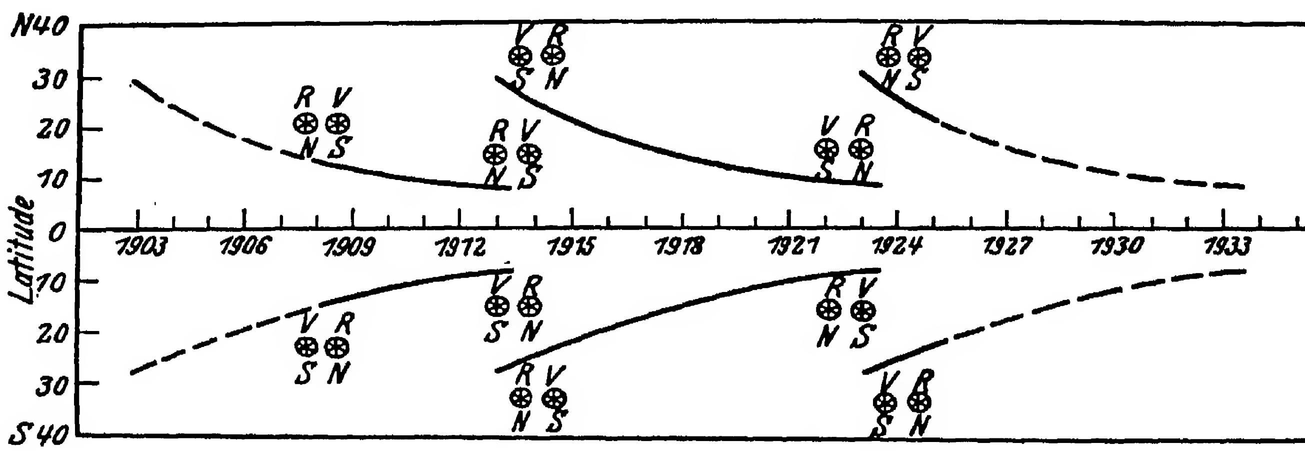

FIG. 110. The law of polarity of sunspots.

entire sunspot period corresponding to the interval between successive appearances at high latitudes of spots of like magnetic polarity, must be considered to be of double duration. This cycle of about twenty-three years may be called the "magnetic period" of sunspots, to distinguish it from the period of half this duration for the other manifestations of solar activity. Also the relative numbers, or the sunspot areas (page 73), possibly undergo the influence of this period of double duration, as found by Turner from analysis of Wolf's relative numbers.

Relationships between Hydrogen Vortices and Sunspots. Origin and Life of Sunspot Groups

The extensive disturbed zones found with the spectroheliograph in the hydrogen atmosphere surrounding sunspots

and which, by reason of their vortex appearance, led Hale to the discovery of the magnetic fields, may be due to actual hydro-dynamic vortices, resembling cyclones, or to electro-magnetic phenomena in which the particles moving in the solar atmosphere are compelled by the magnetic fields of the spots to follow their lines of force.

The statistical researches carried out on spectroheliograms made at Mount Wilson show that no relationship exists between the polarity and direction of the vortex on the various spots, and moreover, that after reversal of the magnetic polarity in two successive minima, there is no corresponding reversal in the direction of the respective hydrogen vortices. These results do not therefore support the electro-magnetic theory. Besides, on the same spectroheliograms it has been found that 81 per cent of the northern vortices and 84 per cent of the southern vortices show the same direction as terrestrial cyclones. This fact, together with the circulatory movements of the solar atmosphere above sunspots (page 192), suggests that the phenomenon of vortices is of an electro-dynamic rather than of an electro-magnetic nature, and that the direction of the rotary movement is generally determined, not by the direction of the vortices of the underlying spots but by an eastward or westward deviation, due to solar rotation, of currents flowing northward or southward in the solar atmosphere towards the centre of attraction above the spots.

When discussing the Evershed effect we saw that it is possible to determine on sunspots both the radial and the tangential components of the movement of metallic vapours. It is clear that from the knowledge of these components we can calculate the actual movement of these vapours from the centre of the spots towards the exterior: we find that in general this motion follows the laws of a "logarithmic spiral." From this calculation, or from simple determination of the tangential components, we can ascertain the direction of rotation of vortices at the spectroscopic level of these metallic vapours.

As already stated, the tangential components are always inferior in absolute value to the radial components and show, in the series of observations carried out at Arcetri, a well-defined rotary movement (with a percentage of 50 per cent), giving the direction of the vortex; in other cases the components

at the two edges of the penumbra have the same sign, and hence, even if we may sometimes presume their direction when they are not equal in absolute value, we cannot describe the phenomenon as a real vortex but only as a trailing of vapours in a certain direction, which is plausible when we remember the proper motions in longitude established in sunspots.

When comparing the directions of the vortices deduced from these measurements with those found from spectroheliograms made in hydrogen light and the polarities of sunspot nuclei determined at Mount Wilson (page 211), it is found that the great majority of the vortices at the level of the metallic vapours of the reversing layer are of opposite sign to those of the upper hydrogen level. Whilst, therefore, as is known, the hydrogen vortices are for the most part left-handed in the northern hemisphere, those of metallic vapours are right-handed, and vice versa in the southern hemisphere.

In nearly all cases the spots examined are the leading components of the bipolar groups (indicated as βp in the Mount Wilson classification), and hence it must be concluded that in the cycle 1922–33 the preceding spots of each bipolar group, which have southern or negative polarity in the northern hemisphere, show a right-handed vortex opposite to that shown by hydrogen at the level of the $H\alpha$ flocculi.

The problem of the electric charge dominating in sunspot vortices and of the direction of the vortices themselves has been discussed several times by Hale, who had occasion to write:

"We are not yet able to determine with certainty the sign of the electric charge dominating in the vortices of sunspots. If it is always the same, the vortices of the leading and following components forming the bipolar groups must rotate in opposite directions. Moreover, the polarities of opposite sign of corresponding spots (leading or following) in the same hemisphere in successive cycles, must also indicate opposite directions of the vortices. A series of observations of the Evershed effect at low levels in bipolar spots is necessary for solving this problem and thus determining the sign of the prevailing charge. This, however, on the hypothesis that the Evershed effect at low level

actually does represent the vortex of the spots, which is still uncertain."

Bjerknes, too, says in regard to this matter:

"We do not know what agreement exists between the direction of rotation and the sign of the magnetic field; a reliable determination of this agreement would be of fundamental importance to the theory of sunspots and perhaps also to magnetism."

In the series of observations made at Arcetri it was impossible to carry out determinations for the following components of a bipolar group, as they seldom have nuclei of sufficient magnitude to permit of photographing the spectrum, and hence we cannot say whether the direction of the vortex on the following component is reversed with respect to that of the leading component, nor of course is it possible to say anything as to the change of direction from one cycle to another.

Nevertheless, we may observe with Bjerknes that, on account of the sun's rotation, the efflux of vapours would suggest a spiral character, which may explain the spiral structure that often manifests itself in the upper layers. Since this structure is determined by the direction of the sun's rotation and not by that of the underlying photospheric vortex, there is no reason whatsoever why these spiral structures should vary when the magnetic polarities are reversed at the commencement of a new cycle of spots.

We must thus conclude that also the rotary or cyclonic movement of the metallic vapours is closely related to that of the hydrogen vortices about them, at any rate in the leading components of a bipolar group (βp), and that, since the movement is of a hydrodynamic nature, it will follow the phenomena occurring in terrestrial anticyclones, which are likewise formed by two opposite systems of vortices with radial and vortex motion, the one being superimposed upon the other.

This hypothesis might be corroborated by the fact that the rotational movements of the metallic vapours are rather slight and uncertain, often being found to trail in a single direction. This is in good accordance with Milne's calculations based on the hydrodynamic hypothesis, which show that the effect

of efflux predominated over the rotational effect, since the cyclonic motion brought about by the sun's rotation is negligible as compared with the velocity of efflux. "The essential point," writes Milne, "is that the efflux constitutes a necessary part of the structure of the spots, whilst the cyclonic rotation is only an accidental part of it."

How the hydrodynamic phenomenon is associated with electromagnetic effects resident in the spots, with the sign of the predominant charge and with polarity reversal, has still to be accounted for by future experimental and theoretical researches.

The complex of these phenomena presented by sunspots tends to explain the origin and life of the groups of spots. The development of these groups generally proceeds in a definite manner, although occasional exceptions are noticed among small groups of brief duration.

At its appearance on the photosphere a typical group consists of two small spots with opposite polarities, situated at about the same distance from the solar equator and separated from each other by three or four degrees of longitude. The initial development is comparatively rapid, and the group attains its maximum area in about a week. During this stage the spots develop within the group itself, usually near the main components, but sometimes also in the space between them. As soon as the area of the group increases, the main components recede from each other until they are ten or more degrees apart in longitude. The western spot is generally slightly larger than the eastern one, and is more symmetrical and less subject to rapid changes.

The phase of maximum activity lasts only a few days, after the group begins to decline at a slower rate. The first to disappear is the eastern or following component, which from the outset proves to be the less stable component of the group: usually its disappearance takes place with the subdivision into small spots which gradually diminish in size. After another week or so the western or leading component is all that remains of the group. This component may last for many weeks or even months, diminishing gradually in area but seldom decomposing as did the following component of the group.

We may notice, particularly in spectroheliograms taken in

calcium light, that the first indication of the formation of a new group occurs together with the appearance in the upper solar atmosphere of luminous flocculi covering the entire region of the group, usually a day or two before the spots are seen. After the disappearance of the following components in the group of spots the flocculi remain, so that even if no previous observations have been effected a spot may be identified by the leading component of a group, from the position it occupies in the calcium flocculi above the group. As soon as the residual spot diminishes the flocculi also diminish, especially those following the spot, until finally they are situated symmetrically with respect to the underlying spot.

As already stated (Fig. 93, page 186), there are at least five levels distinguishable in the solar atmosphere. The lowest is the level of the vortex producing the magnetic field. Above this, in the photosphere, is the spot which we see and photograph directly. Between this level and that of hydrogen, in which spectroheliograms are obtained with the $H\alpha$ line, is the region that can be photographed with the other intense lines of the solar spectrum. The parts of the H and K lines indicated as H_2 and K_2, which are relatively bright near sunspot groups, represent the highest levels of this region. Still higher is the level photographed with the $H\alpha$ line and the level corresponding to the central components H and K, which is the highest of all in the chromosphere.

At these maximum levels, as already stated (page 121), we can observe (particularly with the spectrohelioscope) masses of luminous hydrogen which are thrown out by the spot, whilst dark clouds of colder hydrogen are formed above it and sucked into the vortex. These hydrogen flocculi are those which are often seen to curve in spiral formation around the spots.

At the commencement of the life of a group, especially when there are many spots, these vortices may appear rather confused, but as soon as the group reaches its final stage, viz. when there is only one spot left, the vortices are very conspicuous and perfectly symmetrical.

General Magnetic Field of the Sun

The Zeeman effect, sometimes extending considerably beyond the limits of the penumbra, and the configuration of the

hydrogen flocculi, suggested that magnetic fields over great areas could exist in regions far from the visible spots. Moreover, the general configuration of the corona (Fig. 114, page 232) would seem to indicate that the sun as a whole may be considered a magnet; indeed, the coronal rays, especially those in the neighbourhood of the poles, show a distribution similar to that of the lines of force in a magnetized sphere.

Then again, the shape and velocity of prominences receding from the sun seem to be subject, as Deslandres observed, to the influence of its magnetic field. On the basis of these considerations Hale examined the general magnetic field of the sun, which is analogous to that of the earth. Since in any case this field, compared with that of sunspots, could not be of very great intensity, it was first necessary to investigate where the Zeeman effect should appear at its maximum in the lines of the reversing layer, and then to find a suitable method of observing it.

There was indeed reason to expect, not a real and proper separation of the spectral lines as on sunspots, but only a widening, and hence a large dispersion was required, like that given by the 75-ft. spectrograph of the great solar tower of Mount Wilson, using the third order of the spectrum, with a linear scale of 5 mm/A.

With a polarizer of the type described (page 196), viz. one made of numerous quarter-wave strips, each 2 mm wide, in conjunction with the Nicol, if the widening existed one should see the line shift alternately to the right or left of the mean position when passing from one strip to another, according as that particular strip transmitted the one or the other component. As in any case the amount of the shift is very slight, being of the order of 0·001 A, i.e. 0·005 mm on the plate, their measurement had to be effected with the aid of a micrometer consisting of a small plate with plane parallel faces (page 197).

The basic hypothesis propounded both for executing the observations in the most profitable manner and for establishing the formulae suitable for expressing the characteristics of the magnetic field, was simply that of considering the sun's magnetic field to be similar to that of the earth. The first measurements effected on a few lines of the spectrum of a solar region

situated on the central meridian, proved, in accordance with that hypothesis, that the shift of the lines is very slight and of opposite sign for the latitudes of 45° north and south.

The characteristics of the field to be determined are: the *inclination* i of the magnetic axis with respect to the axis of rotation, the *longitude* λ of one of the magnetic poles with reference to the central meridian, reckoned in the direction of the sun's rotation, and the maximum *field intensity*.

When the existence of the general magnetic field had been established on the basis of these initial measurements, the Mount Wilson astronomers selected some thirty spectral lines of an intensity ranging between 0 and 5 of Rowland's scale, which were known from laboratory researches to give considerable separation of the components under the influence of the magnetic field. The shifts measured for these lines, along the central solar meridian from the north to the south pole, are represented by a curve, as had been anticipated, with a positive maximum at 45° north latitude and a negative minimum at 45° south latitude.

From these curves, determined at different epochs, for different positions of the sun's axis of rotation, we obtain with simple formulae of spherical trigonometry the inclination i and the period of rotation P of the magnetic axis around the axis of rotation, and the intensity of the field H_p at the magnetic pole.

From observations carried out at Mount Wilson from 1912 to 1914 at the epoch of minimum solar activity in order to profit by relatively tranquil conditions of the photosphere, Seares deduced the following results:

$$i = 6{\cdot}0^\circ \pm 0{\cdot}4^\circ$$
$$P = 31{\cdot}52 \pm 0{\cdot}28 \text{ days.}$$

The intensity of the field varies from 10 to 55 gauss according to the lines considered, and seems to diminish rapidly with the height, owing to which, whilst the intensity of 55 gauss would correspond to lines attaining a level of 250 km above the photosphere, that of 10 gauss corresponds to lines attaining a level of about 400 km. Further observations are needed on this point, among other reasons because, as we have seen (page 176), the lines of higher level are as a rule more intense,

and for them it becomes more difficult to measure the slight shift due to the Zeeman effect. At any rate it may now be concluded that only lines in a shallow layer are influenced by the magnetic field in an appreciable manner permitting of measurement by these methods.

After the epoch mentioned the observations were and are still continued at Mount Wilson with a view to determining possible variations in the constants of the magnetic field which may also be related to the phases of solar activity. In the meantime it may be stated that the sign of the general field is still that which existed at the commencement of these determinations, even when the magnetic polarities of sunspots changed their sign at the commencement of each new cycle.

CHAPTER IV

HOW THE OUTERMOST ENVELOPES OF THE SUN ARE STUDIED DURING ECLIPSES AND IN FULL SUNLIGHT

Total Eclipses of the Sun

When the moon's disc entirely covers that of the sun during a total eclipse of the sun, we can see in addition to the chromosphere another very extensive luminous envelope which is distributed in a very peculiar manner around the solar disc, and is called the "corona."

As it is of course very important to ascertain the shape and physical characteristics of this outermost envelope, efforts have been made to study it not only during the brief moments afforded by solar eclipses but, by direct or indirect methods, to observe it in full sunlight as well. Compared with the photosphere, however, the corona is very faint: in its innermost parts it does not shine more brightly than the surface of the full moon, which is six hundred thousand times less luminous than that of the sun. The corona is about equal in intensity to the illuminated sky at eight or ten degrees distance from the sun; but nearer the edge of the sun, light from the photosphere scattered by our atmosphere is so predominant that it is very difficult to photograph the corona in full sunlight.

Several attempts made by Hale and other investigators in the past (for example with the spectroheliograph conveyed to the tops of mountains at a considerable height above sea-level) to avoid the lowest and most turbid layers of the terrestrial atmosphere, have proved unsuccessful. It is only recently that Lyot has succeeded in photographing the inner corona and the most intense lines of its spectrum in full sunlight.

He was able to obtain this result by constructing an instrument in which the diffusion of light caused by its optical parts is reduced to a minimum. The coronagraph constructed by Lyot consists of a plane-convex lens of 13 cm diameter and 315 cm focal length, made of special glass prepared with great

care in order to avoid scratches, bubbles, etc. This lens is placed at *A* and forms a solar image on a disc *B* of blackened metal, which extends about 15″ beyond the solar disc. A field lens *C* placed behind the disc forms an image *A′ A″* of the lens *A* on a diaphragm *D* in whose centre a small screen *E* is mounted. The edge of this diaphragm intercepts the light diffracted by the edge of the first lens. The small screen intercepts the light of the solar image produced by reflection on the faces of this lens. Behind the diaphragm and screen an object-glass *F*, protected from the diffused light, produces at *B′ B″* an achromatic image of the corona. These devices are fixed on a slide *M* that can be shifted to permit adjustment of the solar image on the screen. All these optical parts are enclosed in a wooden tube *G*, 5 m in length, whose inner

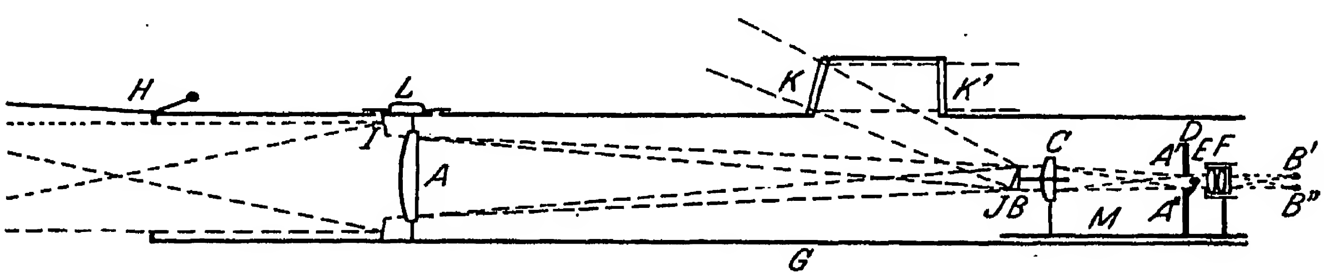

FIG. 111. Diagram of the Lyot coronagraph.

walls are sprinkled with dense oil; the tube is closed by a lid *H*, which is opened only during the observations; the lens *A* with its framing closes the tube completely in order to avoid air currents. The lid *H* is of silvered metal; a concave diaphragm *L* and a disc *J*, also silvered, reflect the unused radiation outside the apparatus in order that the air contained in the tube of the coronagraph shall not heat up, as this would impair the definition of the images. The radiation reflected by the diaphragm returns through the aperture of the lid, whilst the light reflected by the silvered disc passes through the windows *K* and *K′*.

In order to obtain from this coronagraph all the results that Lyot expected it was necessary to use it at a high position, and the point selected was on the Pic du Midi, at a height of 2,870 metres, where there is a branch of the Paris Observatory. Under these conditions and with a simple eyepiece provided with a red screen, numerous prominences became visible,

some only a few seconds of arc in height, and at their base the chromosphere. With the same instrument Lyot succeeded later, in July 1931, in photographing the corona under conditions of considerable transparency of the atmosphere. We are concerned only with the inner corona, in which, however, can be clearly seen coronal rays extending from 4′ to 7′ beyond the limb. This faint image of the corona is projected on a luminous background whose brightness is about 4 millionths that of the sun.

Lyot is of the opinion that in spite of the precautions taken,

FIG. 112. Prominence on the eastern limb; Sept. 11, 1933, 10 h. 50 m. (Lyot).

the diffusion given by the coronagraph always amounts to the major part of the brightness mentioned, whilst only a small part is due to atmospheric diffusion; hence it is perhaps still possible to perfect such an instrument. At all events it will be understood that eclipses give, and always will give, a more complete view of the corona, especially in its outermost parts, than that obtainable without waiting for an eclipse; the same may be said for observations of the emission spectra of the chromosphere and corona.

Lyot, continuing his experiments, combined with the coronagraph a spectrograph which could easily be transformed into

a spectroheliograph, and with this instrument he was able to photograph the two most intense lines in the green and red region of the coronal spectrum, all around the solar disc. He also found by measurement that near the sun's limb the green line attained at certain points an intensity of 70 millionths that

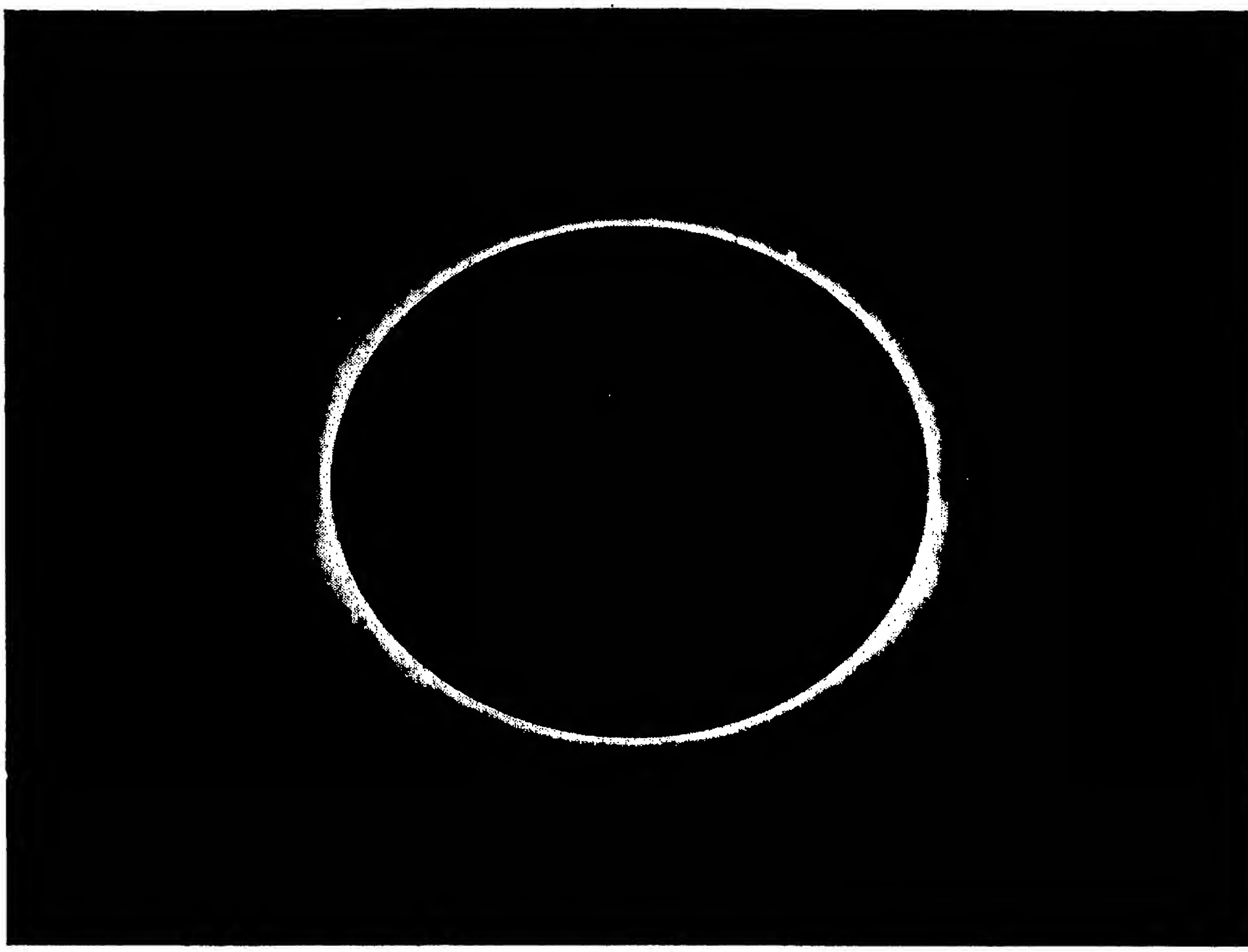

FIG. 113. The inner corona photographed by Lyot, July 6, 1936, 8 h. in full sunlight at the Pic du Midi.

of one angstrom of the continuous solar spectrum, and at other points only 3 millionths. In the case of the coronal spectrum, too, it is clear that far more can be learnt, as we shall see from observations carried out during total eclipses of the sun.

Although the phenomenon of eclipses is of the utmost interest both from the spectacular and from the scientific point of view, there are but few records or descriptions of this grand natural phenomenon of an earlier date than the nineteenth century, because of the very brief duration of total eclipses (which never last longer than a few minutes) and because

of the very limited terrestrial zone within which the eclipse is total. In view of the faintness of the corona it is necessary, in order to see it in its full extent together with the red flames (i.e. with the prominences surrounding the solar disc), that the eclipse be actually total; otherwise, even if but a thousandth part of the sun's disc remains uncovered by the moon, the beauty of the phenomenon, the appearance of the corona and prominences, is completely lost.

After 1800, and especially after Fraunhofer's discovery, the observation of eclipses became increasingly interesting, both because of the phenomenon itself and because of the knowledge which it was realized could be gathered from it regarding the physical constitution of the sun.

The eclipse of 1851 was a memorable one, because it was the first to be photographed with the aid of the daguerrotype. But the eclipse during which the first notable results with photography were obtained by Father Secchi and by Warren De La Rue, was that of 1860. Aided by Pope Pius IX, Father Secchi travelled to the totality zone at Desierto de las Palmas, near Castellón de la Plana, adjoining the east coast of Spain. At the same time the astronomer De La Rue went to Ribellosa, on the west coast, and the two observers obtained good photographs of the eclipse, from which they concluded:

(*a*) that prominences are real objects at the sun's limb and not plays of light, as was believed by some;
(*b*) that the corona is also real; that it is more developed at the equator than at the poles, and even more at 45° than at the equator itself.

Less fortunate was Father Secchi during the eclipse of 1870 that was visible in Sicily, for which he went to Augusta, whilst other Italian astronomers, Tacchini, Nobile and Lorenzoni, were at Terranova.

Whereas Secchi could hardly see the eclipse through the clouds towards the end of its totality, Tacchini and his collaborators were able to confirm the reality of the corona and the presence of the reversing layer. During the same eclipse and under more favourable conditions of the sky, Young made a complete observation of the reversed solar spectrum (flash

spectrum) (page 100), and although he could not ascertain whether all the bright lines occupied the same position in the spectrum as the dark lines, the identity was at first sight evident as regards both the general arrangement and the relative intensity of the lines.

This observation, adds Young, confirms the existence of the continuous spectrum found by Secchi at the edge of the disc, proving Kirchhoff's hypothesis on the constitution of the sun and on the origin of the spectral lines. From these observations, contrary to what Kirchhoff thought, the reversing layer was found to be of small thickness as compared with the size of the sun, as Secchi had anticipated. On the ground of these first observations Father Secchi could also foresee the physical constitution of the corona, his opinion being that it must be composed of substances whose temperature is fairly high, as the corona is luminous. These substances are principally hydrogen, helium and an unknown element in the corona first noticed by Young in 1869, to which was given the name "coronium." As we shall see, coronium is not a new element, the lines ascribed to it being due to known elements radiating in the corona under conditions which are very different to those obtainable in a terrestrial laboratory.

Secchi, too, thought that with some special arrangement of artificial eclipses it would be possible to see the corona in full sunlight, the more so as Tacchini at Palermo thought he saw a trace of it under conditions of exceptional transparency of the sky. Previously Secchi and Tacchini had spoken of a project of observations on Mount Etna in order to place themselves in a still better position. "The skies of Sicily," notes Father Secchi, "are of admirable purity, whereas those of Rome seem dirty and foggy in comparison." The project was to be resumed and carried out several years later by Hale, who, together with Riccò, made his way up Mount Etna for that purpose, but did not attain his object.

During the eclipse of August 18, 1868, which was visible in British India, on the Malay Peninsula and in Siam, Janssen, as already stated (page 137), observed the spectrum of the prominences with the emission lines and, together with Lockyer, paved the way for continuously observing them without waiting for total eclipses.

During the eclipse of 1871 use was made for the first time, at Young's suggestion, of a spectroscope without a slit. With such an instrument in use at the moment of totality the emission lines appeared as luminous rings, whose extent enabled one to determine the height of the various gases on the photosphere. Lockyer found that hydrogen, uniformly distributed around the sun, attains a height of more than 300,000 km, and the green ring due to the hypothetical element coronium a height of 500,000 km.

During the eclipse of 1878, visible in the United States of America, the corona appeared considerably less bright than those of 1870 and 1871 and had a different shape: the polar rays resembled lines of force around a magnetized sphere, and the coronal rays along the equator were of enormous extent. From a mountain in Colorado, Langley was able to observe these rays up to a distance of six diameters from one of the solar limbs, whilst from the other limb they extended as far as twelve diameters.

The mystery of the constitution of the corona became more and more complicated, as one could not imagine how the solar atmosphere, subject as it is to the law of gravitation, could extend to the enormous distance of more than fifteen million kilometres from the sun's surface. The sun was at that time at its minimum of activity, and observers began to suspect that the shape of the corona varied according to the eleven-year cycle.

The eclipse of May 17, 1882, was visible in Egypt with a very short period of totality, and has remained famous because of a bright comet that was seen and photographed near the sun during totality, whereas it could not be observed before or after the eclipse. At that epoch the sun was at its maximum of activity, and the shape of the corona, like that of 1871, again appeared almost rectangular, like a star, the long equatorial rays and the intense and short curved polar rays being completely absent.

During the eclipse of 1883 Janssen, continuing the observations of the coronal spectrum, concluded that its base consisted of the complete Fraunhofer spectrum, and that for this reason there must be a large amount of reflected solar light in the corona. Since the coronal substance is known to be highly

rarefied, it follows that these regions must be rich in cosmic matter in the state of corpuscles which reflect solar light.

For eclipses later than 1890 increasingly powerful instruments have been used, both for direct photography of the corona and for that of its spectrum, especially by the astronomers of the Lick Observatory and by Lockyer, who thus succeeded in clearly separating the spectrum of the corona from that of the chromosphere.

During the eclipse of May 28, 1900, visible in the United States and in Europe, a very large number of photographs of the inner and outer corona were obtained with instruments of short and long focus, and very good photographs of the flash spectrum and of the corona were taken with large prismatic cameras and flat concave gratings; with the bolometer Abbot measured the radiation of the corona at different distances from the solar limb. Well known, too, on account of the observations and photographs gathered, are the eclipses of 1905, 1914 and 1918. At these eclipses it was confirmed that the corona varies in form with the solar cycle.

The researches during the eclipses of 1919 and 1922 were effected chiefly with a view to proving the deviation of light in the sun's gravitational field, predicted by Einstein's theory of relativity, which cause small shifts in the position of stars in the vicinity of the sun at the moment of the eclipse. Two expeditions were sent out by the Greenwich and Cambridge Observatories to observe the eclipse of 1919, one to Brazil, the other to Principe Island in the Gulf of Guinea (West Africa). From measurements of the photographs taken, the first confirmation of Einstein's prediction was obtained. This was repeated, with still richer material obtained at the eclipse of 1922, by the Lick Observatory expedition to West Australia.

Commenting on the results obtained by that expedition, Campbell and Trumpler wrote:

"Having guarded our results, by means of the check-fields observations, against any systematic errors of instrumental character, or errors due to the photographic process or to the method of measurement, and having found that abnormal refraction in the earth's atmosphere must be rejected as a possible explanation, the conclusion seems inevitable that the observed star displacements are due to a bending of the light-

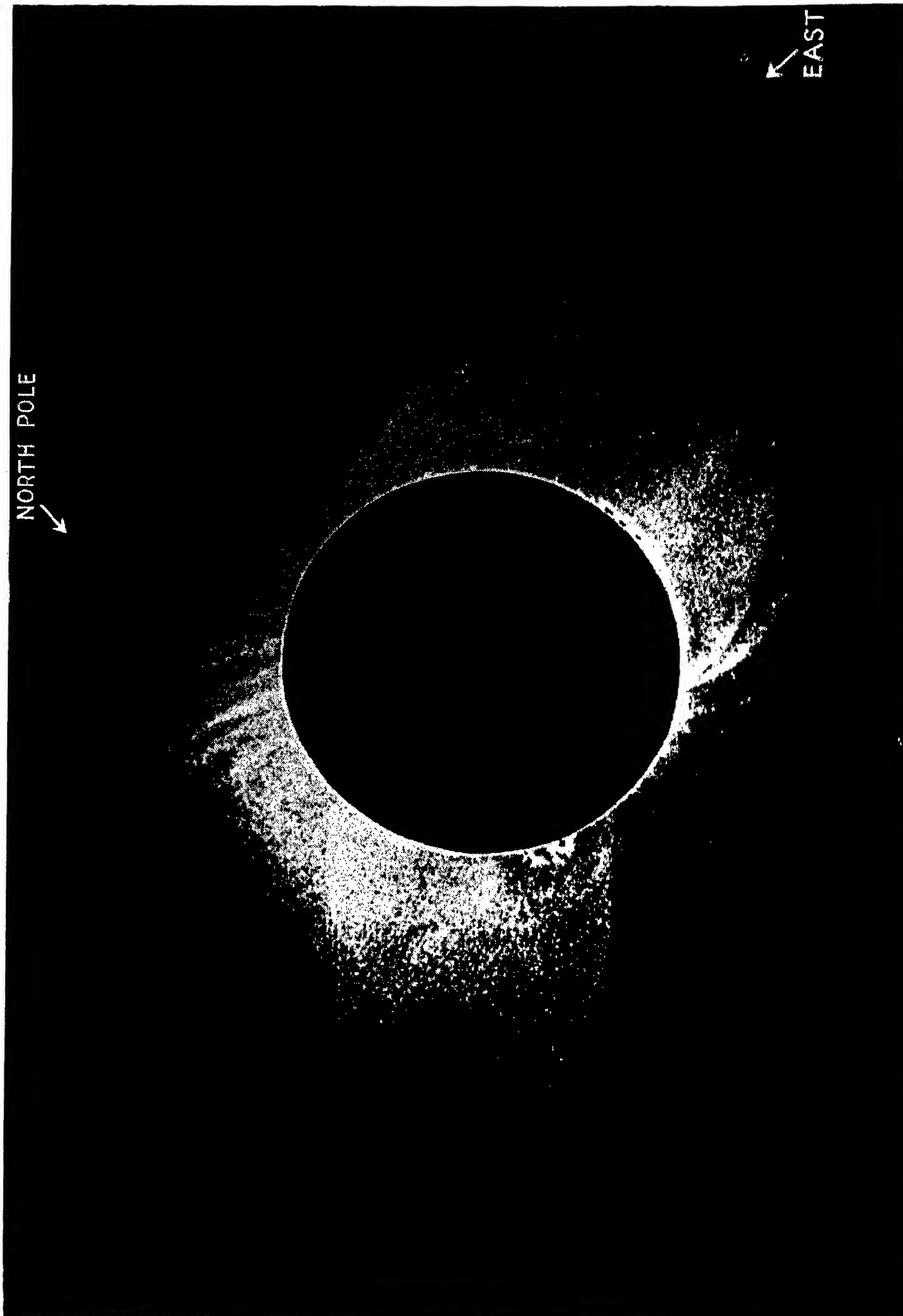

FIG. 114. Eclipse of August 21, 1914, observed by the Italian Mission in the Crimea. Equatorial type. (Drawing by Taffara from photographs.)

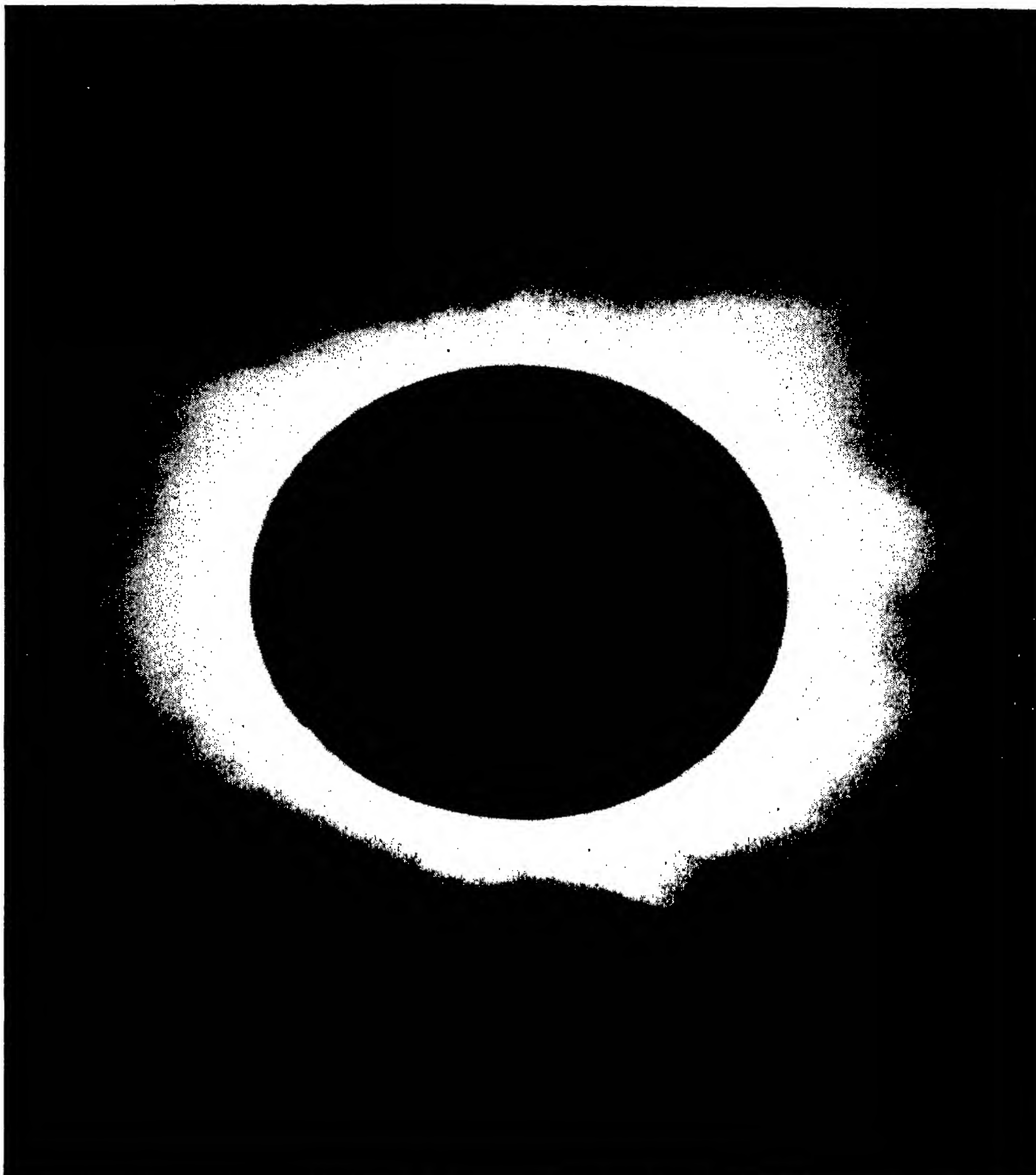

Fig. 115. Corona of January 24, 1925, exposure 15 sec.
(Photographed by the American Mt. Wilson Mission at Middletown, Connecticut.)

rays in the space immediately surrounding the sun. As to the amount of the light-deflections and the law according to which these diminish with increasing angular distance from the sun's centre, the observations agree within the limits of accidental

observing errors with the prediction of Einstein's generalized theory of relativity, and the latter seems at present to furnish the only satisfactory theoretical basis for our results."

For subsequent eclipses numerous expeditions again made their way to remote parts of the earth to observe them. In spite of the cloudiness of the sky, which several times prevented

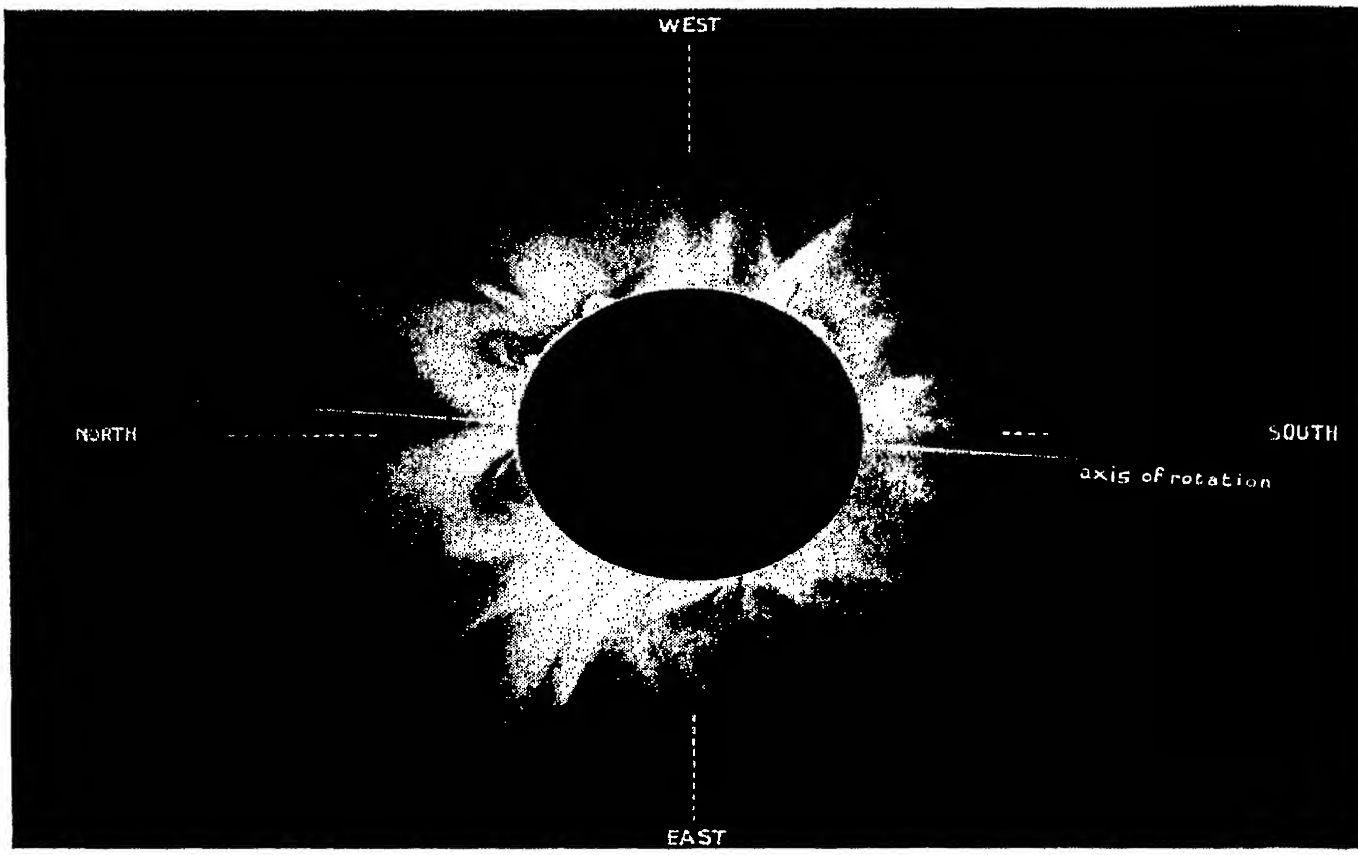

FIG. 116. Corona of January 14, 1926. Polar type.
(Observed by the Italian Mission in Oltregiuba; drawing by Taffara from photographs.)

any observation at all, further photographs and important results were obtained, also with the use of plates sensitive in the red region of the spectrum, which thus enabled us to extend our knowledge of the flash spectrum and coronal spectrum.

In the eclipse of 1926, Stetson of the Harvard Observatory and Coblentz of the U.S. Bureau of Standards were able to measure the radiation of the corona in Sumatra with the same apparatus with which they had made good observations during the eclipse of 1925 which was visible in the United States. They ascertained that the light of the corona in 1926 was

40 per cent stronger than in 1925, which indicated a probable increase of its intensity as a result of an increasing number of spots.

For the same eclipse Mengarini, Horn D'Arturo, and Taffara went to Oltregiuba (East Africa), obtaining photographs of the corona, which were compared with those obtained two and a half hours later by the English mission in Sumatra. Several

FIG. 117. Station of the Italian Mission for observation of the eclipse of June 19, 1936, at Sara (Orenburg District, U.S.S.R.).

changes were detected in the coronal streamers surrounding a striking prominence.

In the eclipse of June 29, 1927, which was visible from the Scandinavian Peninsula and from England, similar observations were obtained, good photographs showing the corona to be of the maximum or circular type, the sun then being exactly at the maximum period of its activity.

For the eclipse of August 31, 1932, numerous expeditions travelled to the totality zone, which crossed the western part of Canada and the United States. The weather was on the whole not very favourable, but several expeditions were nevertheless able to develop their programme.

The eclipse of June 19, 1936, was visible all over the territory of the U.S.S.R., from the Black Sea to the Pacific Ocean as far as the Japanese island of Hokkaido. Numerous expeditions went along the totality zone and particularly good observations were carried out by those of the Harvard Observatory, Poulkovo, and by an Italian mission (G. Abetti, G. Righini,

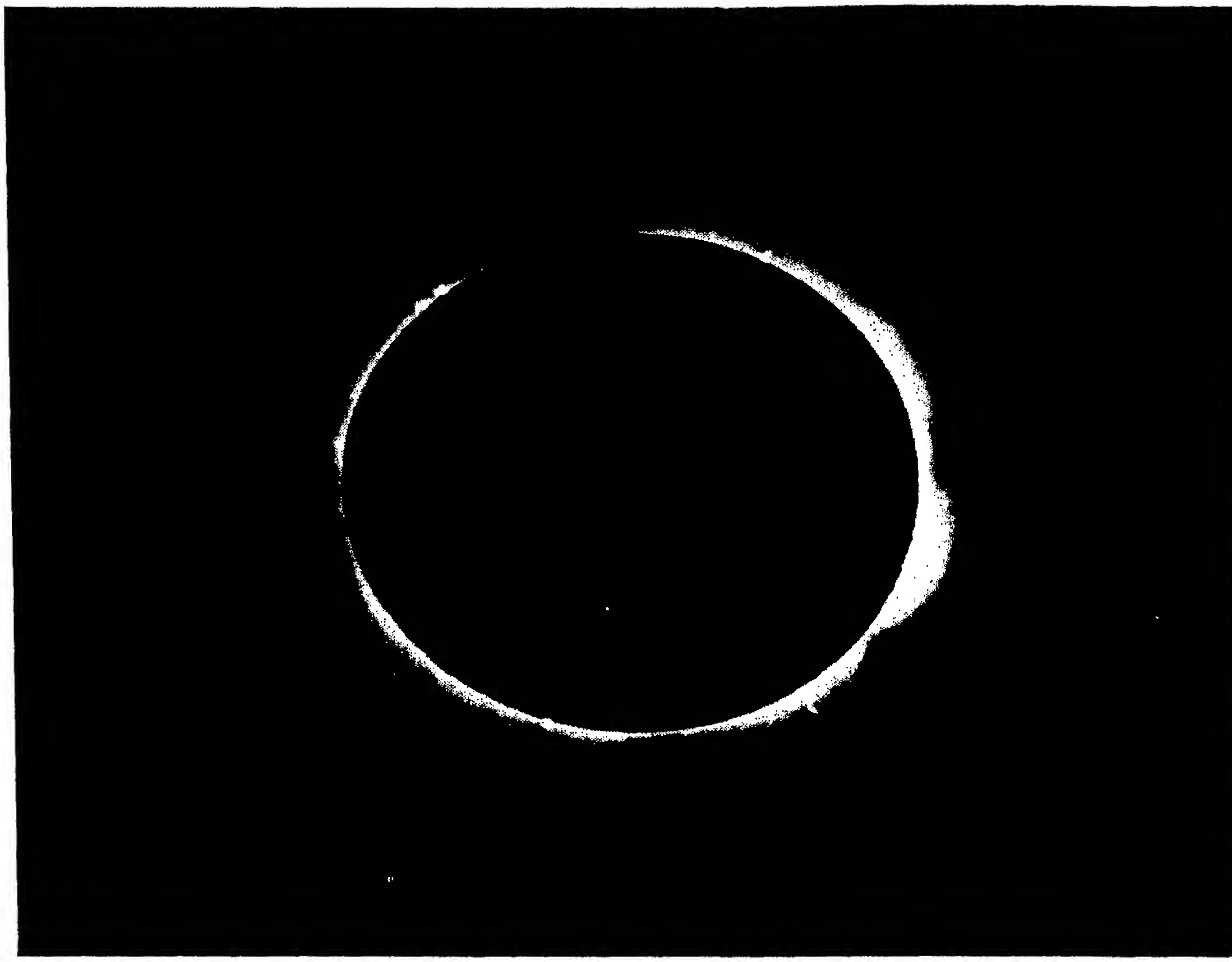

FIG. 118. Inner corona and prominences of June 19, 1936, photographed at Sara by the Italian Mission.

L. Taffara) at Sara in the district of Orenburg. With a double spectrocoronagraph, formed by two telescopes of 1·50 m focal length in conjunction with two prism spectrographs, one for the violet region and one for the visible region, this mission obtained the spectrum of the corona at about one minute of arc from the solar limb. Spectrograms of the emission lines of the chromosphere were obtained with a chromosphere spectrograph fitted with a large grating equipped as an autocollimator,

and photographs of the corona were taken with different exposures by means of a coronagraph with 2·50 m focal

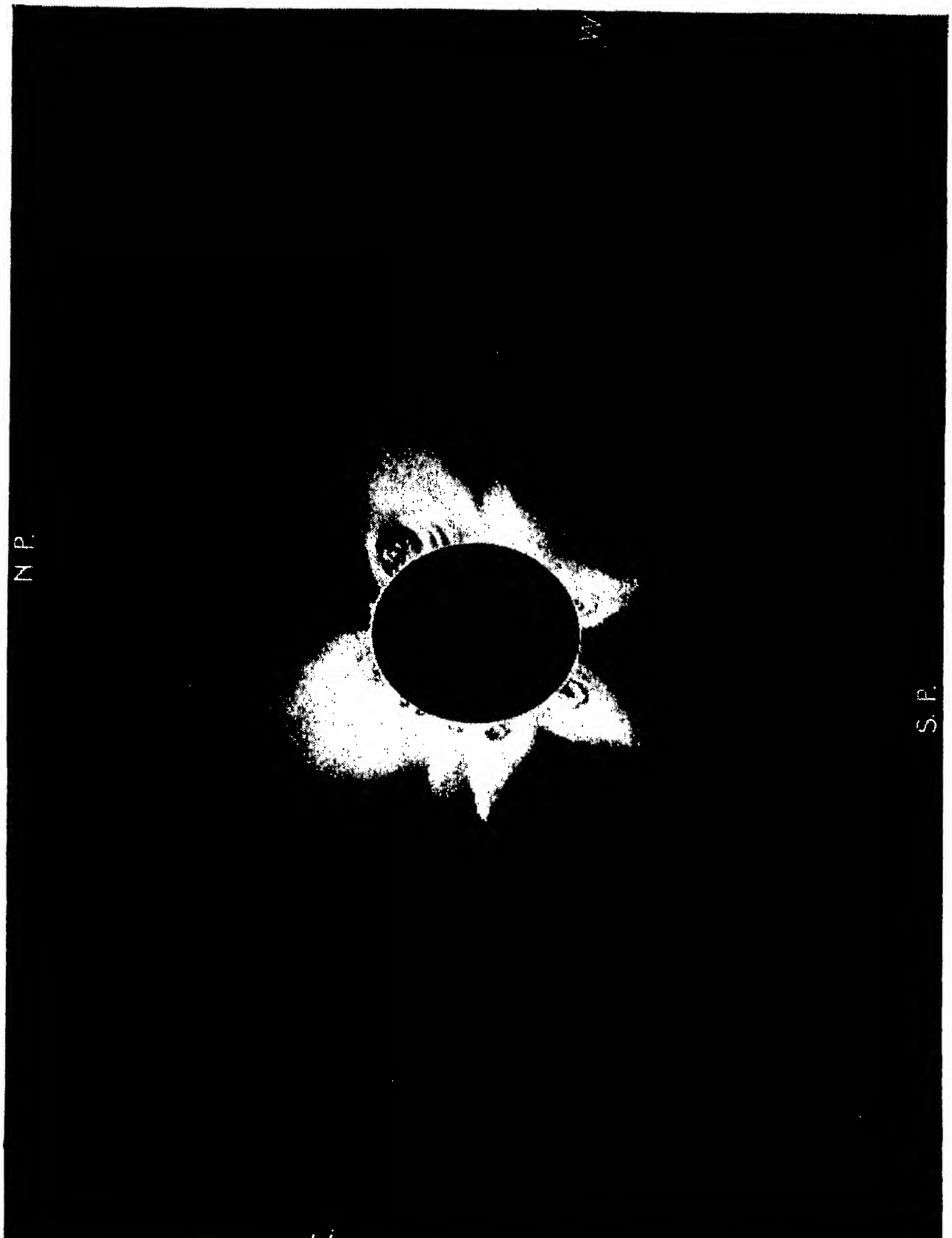

Fig. 119. Corona of June 19, 1936. Intermediate type.
(Observed by the Italian Mission at Sara. Drawing by Taffara from photographs.)

length, using two objectives, one with a yellow and one with a violet filter.

For future eclipses full information is obtainable from Oppolzer's *Canon der Finsternisse* (list of eclipses). This monumental work furnishes particulars of eight thousand solar eclipses and five thousand lunar eclipses, viz. all partial, total and annular eclipses that have occurred since 1205 B.C., and those that will occur up to the year 2152 A.D. For all total eclipses visible during these thirty-four centuries, maps are given which indicate the parts of the earth traversed by the moon's shadow.

Whilst the possibility of observing prominences and the corona without an eclipse may to some extent have diminished the importance of eclipses, it is obvious that they will always be of great utility for studying the sun's outer envelopes, especially when observed with increasingly perfect instruments adapted for rapid use so as to enable observers to take the utmost advantage of the brief moments during which the brightness of the solar disc is completely eliminated by the presence of the moon.

Spectroscopic Study of the Reversing Layer and of the Chromosphere during Eclipses

The spectrum of the reversing layer, which, on account of the manner of its appearance, has been called the "flash spectrum" (page 100), was discovered by Young in 1870. He himself accounted for it on the assumption that the Fraunhofer lines of the ordinary solar spectrum originate in the reversing layer, which must be formed by an envelope some hundreds of kilometres in depth, as is evident from the brevity of the phenomenon.

In the spectrum of the reversing layer the great majority of the Fraunhofer lines are found reversed, but the reversing layer is separated from the chromosphere, and must be considered as its densest and lowest part at the boundary of the photosphere. The first photograph of the flash spectrum was obtained in 1893 with one hundred and sixty-four bright chromospheric lines between K and $H\beta$. S. A. Mitchell, using during the eclipse of 1905 a concave grating of great dispersion without a slit, obtained very beautiful spectra which he subsequently studied in detail, thus considerably increasing our

knowledge of the appearance, extent and intensity of the lines of the chromospheric spectrum. In the eclipse of 1925 Curtis

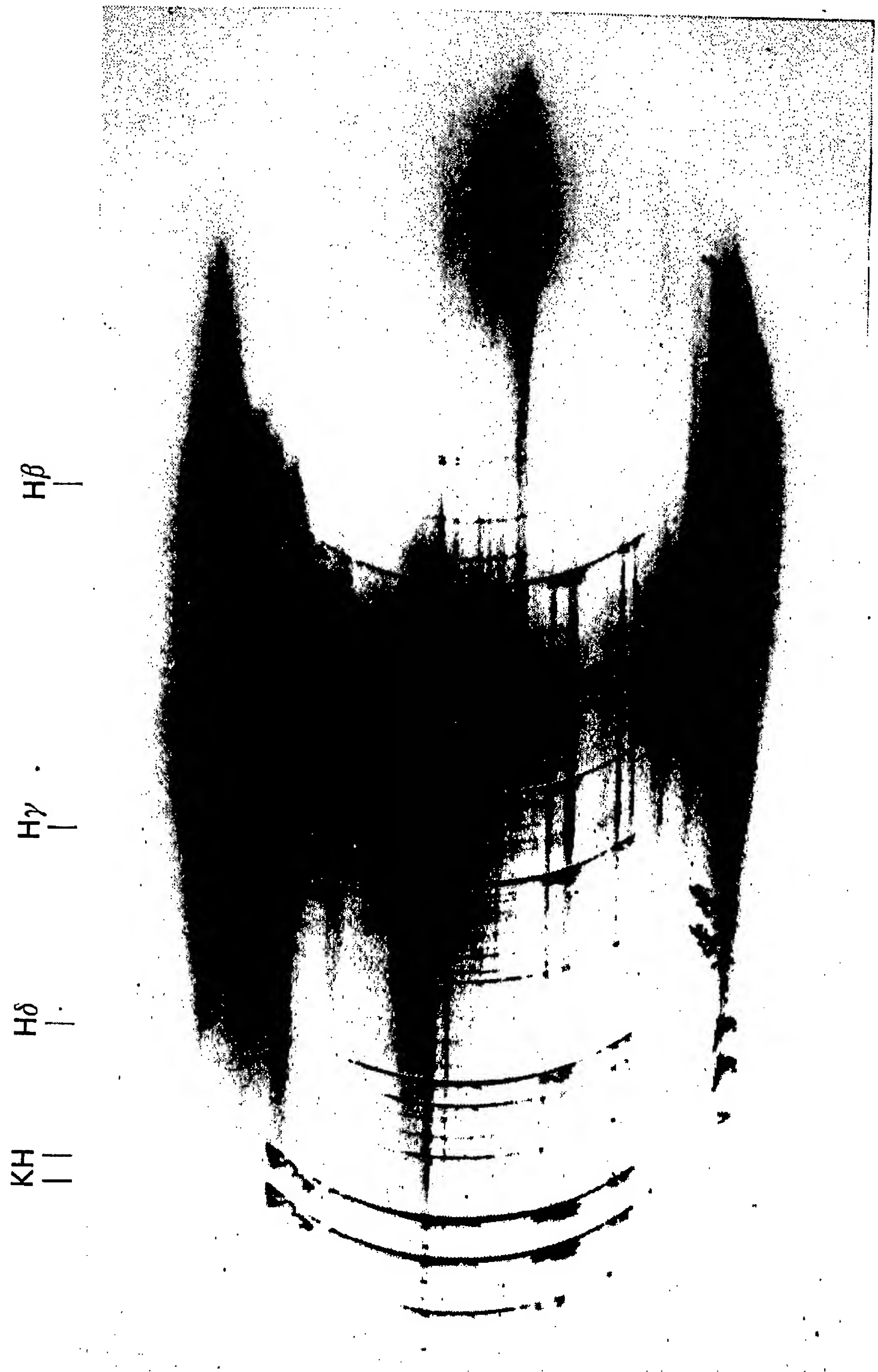

FIG. 120. Spectrum of the chromosphere.
(Photographed with an objective prism by Davidson and Stratton during the eclipse of January 14, 1926, at the moment of second contact; negative image.)

and Burns were able to photograph the spectrum in the infra-red with panchromatic plates, by means of a concave grating of short focus, and in the same eclipse, using the same grating

as was used in 1905, Mitchell photographed the normal spectrum from 3300 A to 7200 A.

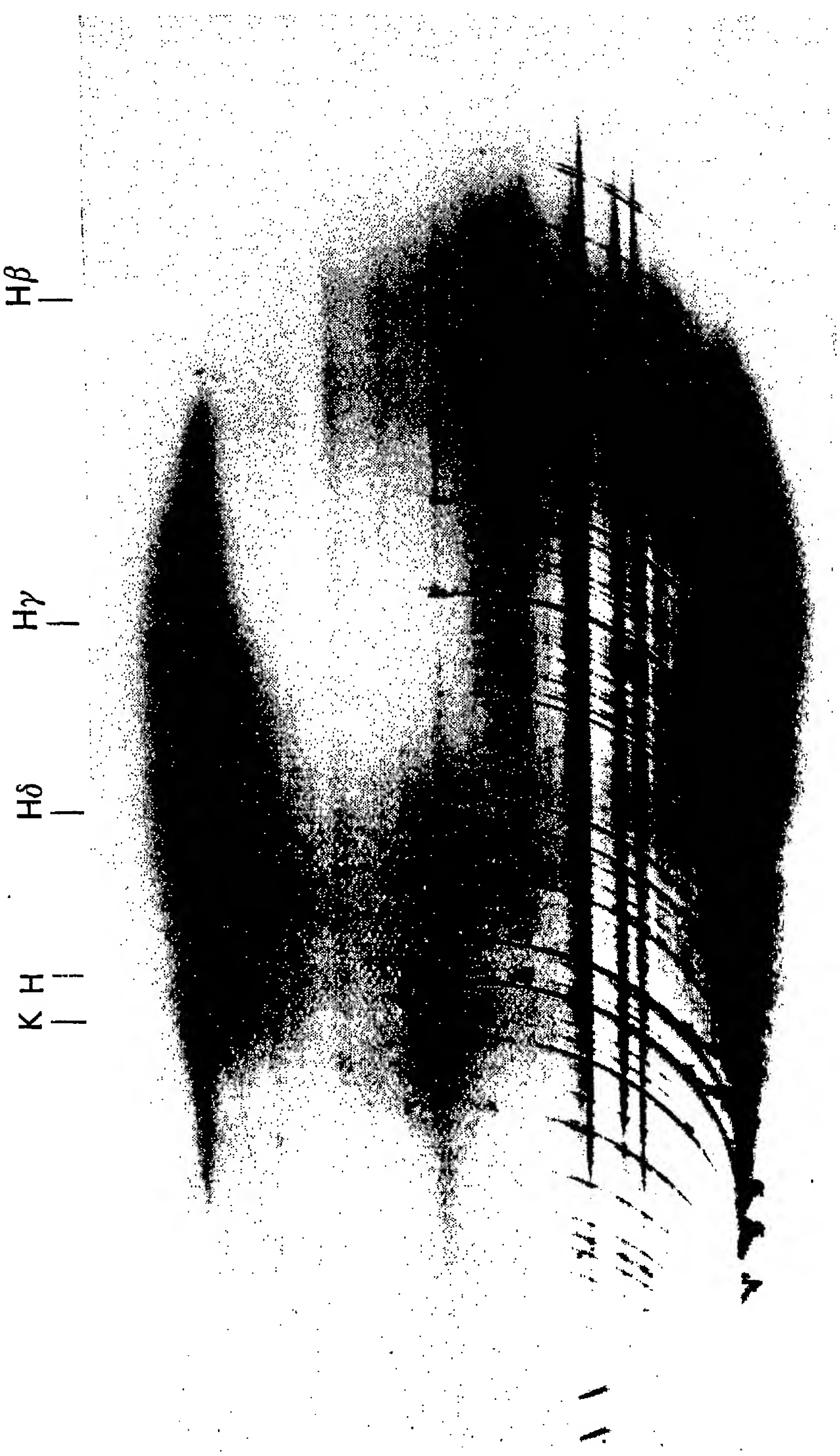

FIG. 121. Spectrum of the chromosphere.
(Photographed with an objective prism by Davidson and Stratton during the eclipse of January 14, 1926, at the moment of third contact; negative image.)

In other eclipses, too, observations have been continued with the aid of spectrographs having a slit or objective prisms, and in this way copious and valuable information has been

gathered. For observing the flash spectrum it is very important to take the exact moment, viz. the moment immediately

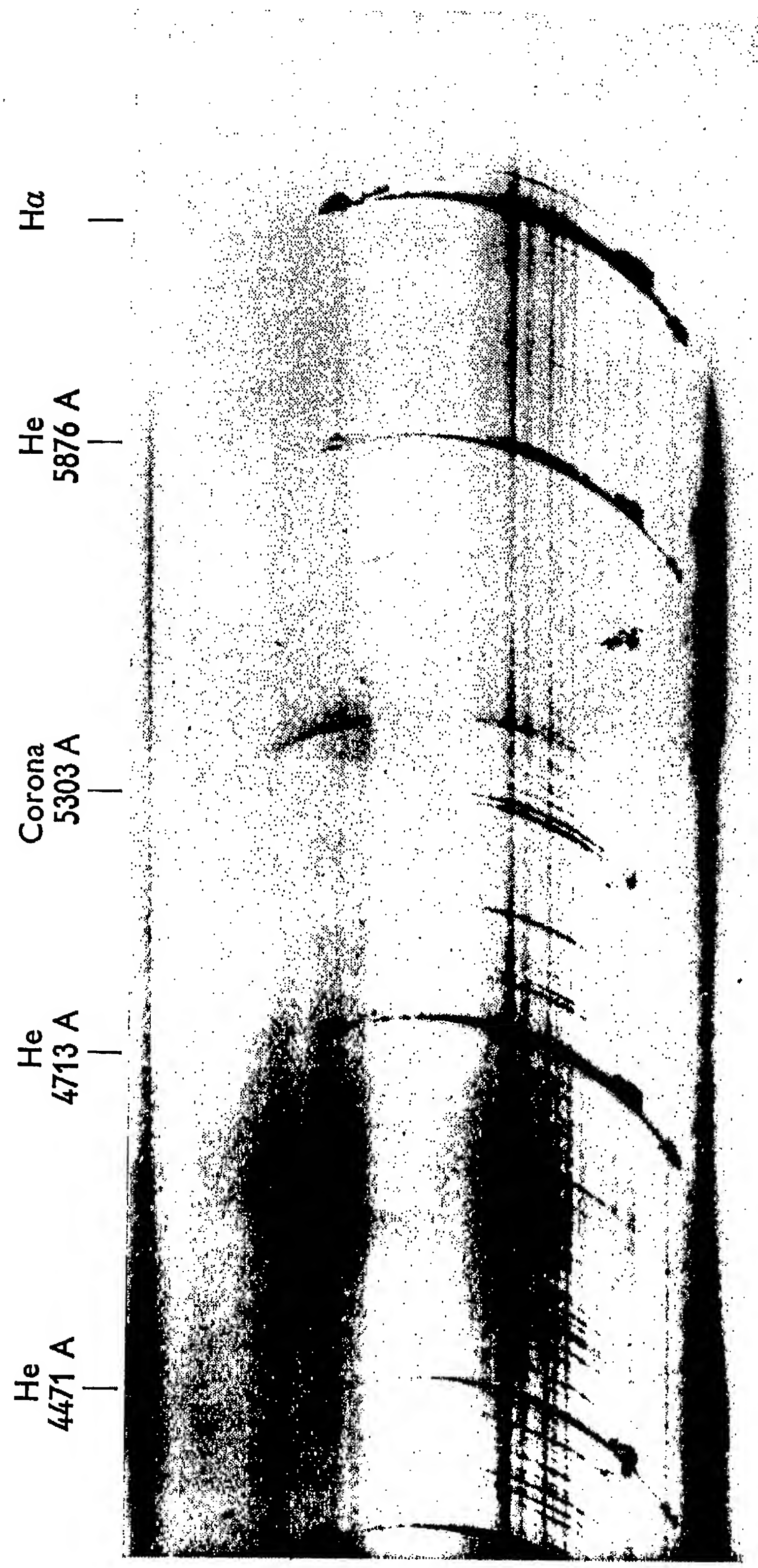

FIG. 122. Spectrum of the chromosphere.

(Photographed with an objective prism by Davidson and Stratton, during the eclipse of January 14, 1926, at the moment of third contact, with the long-focus camera; negative image.)

before the second contact and immediately after the third, in order to see and photograph the chromospheric spectrum as near as possible to the photosphere. Visually, with a

spectroscope, many of the high-level lines are seen reversed several minutes before totality, particularly those situated near the points of the solar crescent, and one can easily estimate the exact moments at which to take photographs of the spectrum of the reversing layer, which will prove to be composed of crescents in increasing numbers the more

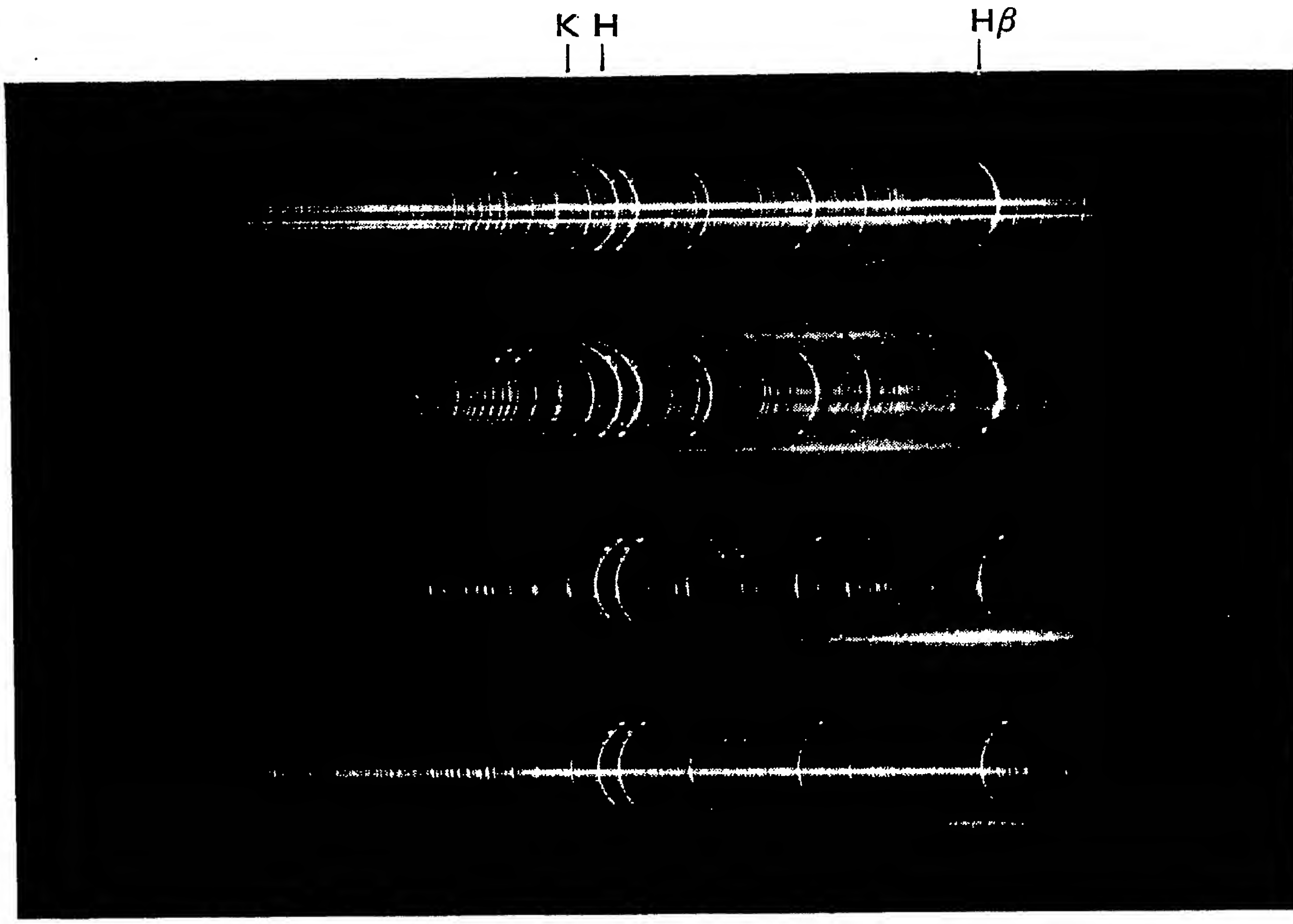

FIG. 123. Spectrum of the chromosphere.
(Obtained with an objective prism by the expedition of the Lick Observatory on August 31, 1932.)

numerous the emission lines, and of increasing area the higher the level of the vapours which produce them.

Another method of photographing the flash spectrum is that called the "moving plate" method, devised by Campbell and used by him and the astronomers of the Lick Observatory. It consists in placing a narrow slit, parallel to the dispersion of the spectrograph, immediately in front of the photographic plate so that only a short section of the central part of the chromospheric arcs may be impressed on the plate. By giving, during the exposure, a uniform movement to the photographic

plate behind the slit in a direction perpendicular to its length, we obtain during the successive progression of the eclipse a photograph of the flash spectrum with its variations at each moment, so that these variations are recorded in a continuous manner.

The first experiments with this method were made by Campbell during the eclipse of 1898 in India, with a plane grating by Rowland. It was successively employed during the eclipses of 1900 and 1905 by Campbell, who obtained during

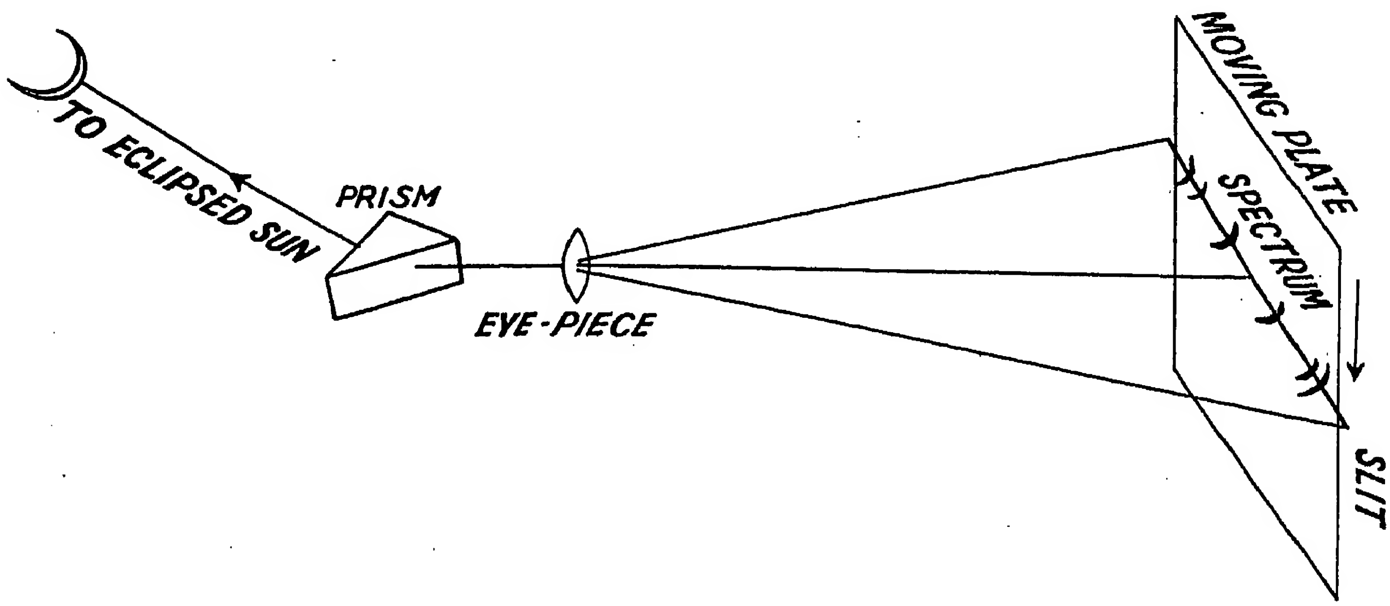

FIG. 124. Diagram of the spectrograph for photographing the flash spectrum with the moving plate (Campbell).

the latter eclipse magnificent photographs of the spectrum from 3820 A to 5300 A, with an objective prism which gave at $H\gamma$ a dispersion of about 6 angstroms per mm. In addition, by means of a spectroscope consisting of two prisms of 60° of ultraviolet glass placed in front of an objective also of ultraviolet glass, the spectrum of the chromosphere was obtained and also that of the corona up to 3400 A. This also affords a method of investigating the variation of intensity of the chromospheric lines with height; on the other hand it is difficult, because of the shortness of the available exposure time, to photograph the faintest low-level lines with the moving plate.

The most marked difference between the chromospheric spectrum and that of the photosphere consists in the relative intensity of the individual lines, viz. in the former

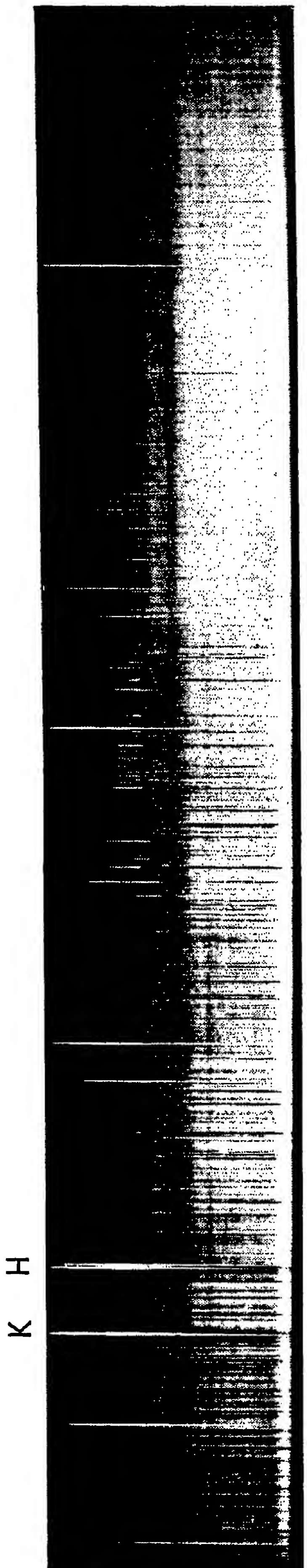

FIG. 125. Spectrum of the chromosphere obtained with the moving plate at Alhama (Spain) by Campbell during the eclipse of 1905.

spectrum the emission lines and in the latter the absorption lines. These intensities have been estimated, as was done by Rowland, with an empirical scale which is not uniform; hence it is difficult to compare values obtained on different plates. Nowadays, with perfected photographic methods, with plates duly calibrated for each exposure and with the aid of the microphotometer, we are beginning to obtain more accurate measurement of the intensity in a uniform scale. For the moment the intensities of the chromospheric spectrum have also been estimated by Mitchell in an empirical scale analogous to that of Rowland.

The characteristic differences in the intensities between the lines of the photosphere and those of the chromosphere are due to the fact that the light of the chromosphere is observed during the eclipse tangentially to the sun's surface, so that other layers are seen which are different from those giving rise to Fraunhofer lines when the centre or limb of the solar disc is observed.

Hence if, for example, there are two different elements, one being of low density and hence extending to a great height above the level of the photosphere, the other being heavier and consequently being contained in a deeper layer, then it is conceivable that the absorption produced by the atoms in the two layers of gas is the same for rays emerging perpendicularly to the sun's surface and at the centre of the disc. Under such conditions it is probable that the two gases give lines of

equal intensity in the spectrum of the photograph. On the other hand, during an eclipse the exposure is progressive, the moon's disc gradually passes across that of the sun, with the result that the exposure of the lower vapours is very short as compared with that of vapours at a high altitude. It is thus evident that, although the two gases may give lines of equal intensity in the absorption spectrum, these lines will not retain their

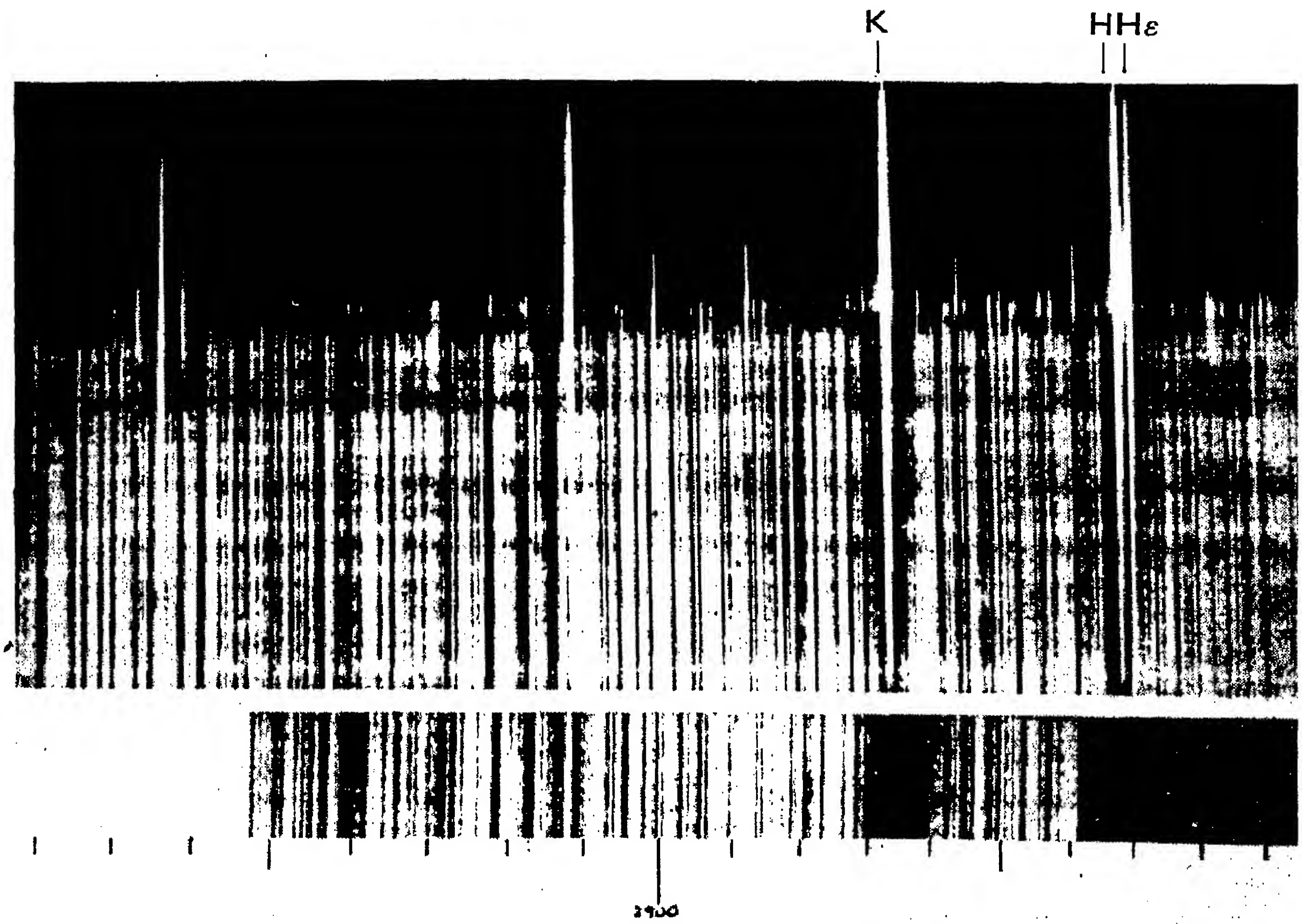

FIG. 126. Spectrum of the chromosphere obtained with the moving plate at Alhama (Spain) by Campbell.
(Enlarged: with spectrum of the photosphere below, for comparison.)

equality in the emission spectrum; the heavy vapour below will produce short arcs in the chromosphere, whilst the others will produce longer arcs of relatively greater intensity.

Whilst there are other reasons which help to bring about greater or lesser intensity, it is certain that the principal factor which influences the difference in relative intensity between the dark and the bright lines is that of the altitude attained by the various vapours. As we have already seen, the H and K lines of *Ca*II and those of hydrogen are the most intense

both in the spectrum of the chromosphere and in that of the disc, for the simple reason that calcium and hydrogen extend to greater altitudes than any of the other elements.

There are thus indeed considerable differences in the intensity of the lines of the two spectra, which, when examined side by side, seem to belong to stars of two different types rather than to the same celestial body. It is just these differences which render the observations made during eclipses so important; the most noteworthy are found for hydrogen and helium.

It is well known that there are no absorption lines of helium in the spectrum of the photosphere, whilst in that of the chromosphere these lines rank among the most conspicuous; moreover, in the photospheric spectrum only a small number of hydrogen lines are seen, whilst in the chromospheric spectrum Mitchell photographed the 34 lines of the Balmer series. Making use of his photographs obtained with gratings and of those of other observers, Mitchell published an extensive *Catalogue of the Chromospheric Lines* from 3066 A to 7065 A. These are compared with those found in *Rowland's Revision*, and the emission intensity for each of them is given in a scale similar to Rowland's scale, whilst the heights attained by the atoms that produce each spectral line are deduced from the amplitude of the chromospheric arcs.

It is found that the intensities of the lines of the photosphere approach more closely to those of the arc, whilst those of the flash approach more closely to those of the spark. In relation to "Draper's classification" it may be stated that whilst the spectrum of the photosphere is quite similar to that of the stars of class *G*, that of the chromosphere belongs to the preceding class *F* (page 325).

With rise of level there is a slight diminution of temperature, but a very rapid diminution of pressure compared with the lower levels; for this reason ionization is most complete at the highest levels. The greatest heights are attained by ionized calcium at 14,000 km above the level of the photosphere; the ionization theory adequately explains the transformation which is observed in the spectrum as it rises above the sun's surface.

A study of the chromosphere analogous to that of Mitchell has been made by Menzel, using the photographs of the flash spectrum obtained with the moving-plate method by several

expeditions of the Lick Observatory. Important conclusions on the constitution and distribution of the elements are deduced by Menzel, the principal points of which we shall refer to here.

The distribution in density of the chromosphere may be ascertained from the relation between the intensities and altitudes of the chromospheric lines or from the intensities measured at different levels. The two methods give the same results. The density gradient of the lower chromosphere for the metallic elements is about that which is to be expected from an atmosphere consisting of pure hydrogen in gravitational equilibrium. The higher levels of the chromosphere seem to be still more dilated. Of two lines, the one having the lowest excitation potential is found to be the more intense in the flash spectrum and it is this one that rises to greater altitudes.

The mean temperature of the chromosphere is of the order of 1000° less than that of the reversing layer. The temperature gradients in the chromosphere are low, probably much lower than the upper limit determined in 0·5° per kilometre. In the chromosphere there is a number of highly excited atoms, greater than that predicted by Boltzmann's law. This excess, which increases with the excitation potential, is very much akin to the so-called "deviation of stellar atmospheres from thermo-dynamic equilibrium," discovered by Adams and Russell, but the effect is greatly intensified in the chromosphere and also becomes greater in prominences.

Menzel and Mitchell also determine the relative quantities of the various elements in the chromosphere, and find that they are about the same as those determined by Russell (page 270) for the photosphere, except for hydrogen, helium and the rare earths, which are found to be more abundant in the chromosphere than in the reversing layer.

Shape and Spectrum of the Corona

Our knowledge of the variations in the shape and spectrum of the corona is still very incomplete, the time available for observing it during eclipses being so short; it should be remembered that, from the day on which helium was discovered in the chromosphere and coronium in the corona, astronomers have had altogether less than one hour at their disposal for

observation. We have stated that, during the various eclipses, telescopes of different types and dimensions were used, which were generally of great focal length, in order to obtain on the plate an image of large diameter of the eclipsed sun. So, according to the exposure taken, the shape and distribution of the coronal streamers and their intensity in the inner corona (viz. the part immediately above the chromosphere, which is sharply distinguished by its greater intensity than the outer corona) can be reproduced in great detail: the outer corona is much fainter and diffused and extends to several solar diameters away from the sun's limb.

The "inner corona" appears as a luminous ring of a pale yellow colour, on which are projected prominences of a vivid hue; the emission lines observed in the spectrum of this corona probably originate in it within a zone of about 250,000 km around the sun. The "outer corona" is of a pearly white colour and consists of faint filaments or rays which diverge more or less rapidly and are curved so as to suggest the trend of the lines of force surrounding a magnetized sphere. Long rays or streamers with a point, consisting of individual filaments, may be forced outward to a distance of several million kilometres from the sun's surface.

Photographs taken at observation posts situated as far as possible from each other in longitude, within the totality zone, do not generally present considerable changes, which proves that the material of the corona is not in very rapid motion, unless such motion takes place along the curved rays and unless there is some considerable active disturbance at the limb. Spectroscopic observations carried out in the spectrum of the corona during the eclipse of 1923, show that the corona moved outwards from two opposite limbs of the sun at a velocity of about 20 km/sec.

It was very soon noticed, both by visual and by photographic observations, how closely the shape of the corona is related to the phase of the eleven-year cycle of solar activity in which the eclipse takes place. At the epochs of maximum sunspot activity the corona is sensibly circular and, as Janssen says, presents the aspect of a gigantic dahlia or of an aureola with streamers that are more developed at high latitudes. At the minimum epochs, on the other hand, the corona is generally

less extensive except around the solar equator, where there are very long streamers which are gradually dissipated in the diffused light of the sky. Langley, observing the eclipse of 1878 at a height of 4300 metres, was able to follow it up to a distance from the sun equal to 24 solar radii.

In the corona of the minimum type there can also be seen, in the neighbourhood of the solar poles, relatively short filaments whose curvature reminds one of the lines of force near the pole of a magnet. At the intermediate epochs, between maximum and minimum, the corona shows an intermediate type: the longest streamers are preferably in the sunspot zone and give this zone a rectangular appearance.

W. J. S. Lockyer, who developed the classification of the forms of the corona, first proposed by Hansky, describing them as polar, intermediate and equatorial, comes to the following conclusions:

(*a*) These different forms of the corona are evidently dependent on that zone of latitude where the centres of action of the prominences are situated;

(*b*) corona of *polar* or irregular type appear when the frequency maximum of prominences is near the solar poles. The *equatorial* type appears when there is only one active centre at the latitude of about 45° in each hemisphere; the *intermediate* type appears when there are two active centres in each hemisphere at the intermediate latitudes (page 154);

(*c*) the special arched shape of some of the coronal streamers is produced by the action of the two zones of prominences situated near the bases;

(*d*) the activity of sunspots apparently has no direct relation to the production of the rays or coronal streamers.

The linear relationship between coronal rays and prominences is more and more convincingly confirmed. Thus, in the photographs of the corona obtained by the Italian mission during the eclipse of 1936, already referred to (page 236), it is evident that single prominences have a very considerable influence on the shape of the corona and streamers, since each streamer has at its base a prominence which visibly affects the accompanying streamer. Over each prominence concentric

envelopes of coronal material are formed which are more or less extensive according to the intensity and area of the prominence.

On the basis of the results furnished by the most recent eclipses, Mitchell further elaborates Lockyer's conclusions and finds that the minimum type of corona, viz. the equatorial corona, presents itself two years before the sun reaches the minimum of its activity, this activity being manifested by sunspots and prominences. Similarly, the maximum or polar type of corona commences two years before the maximum

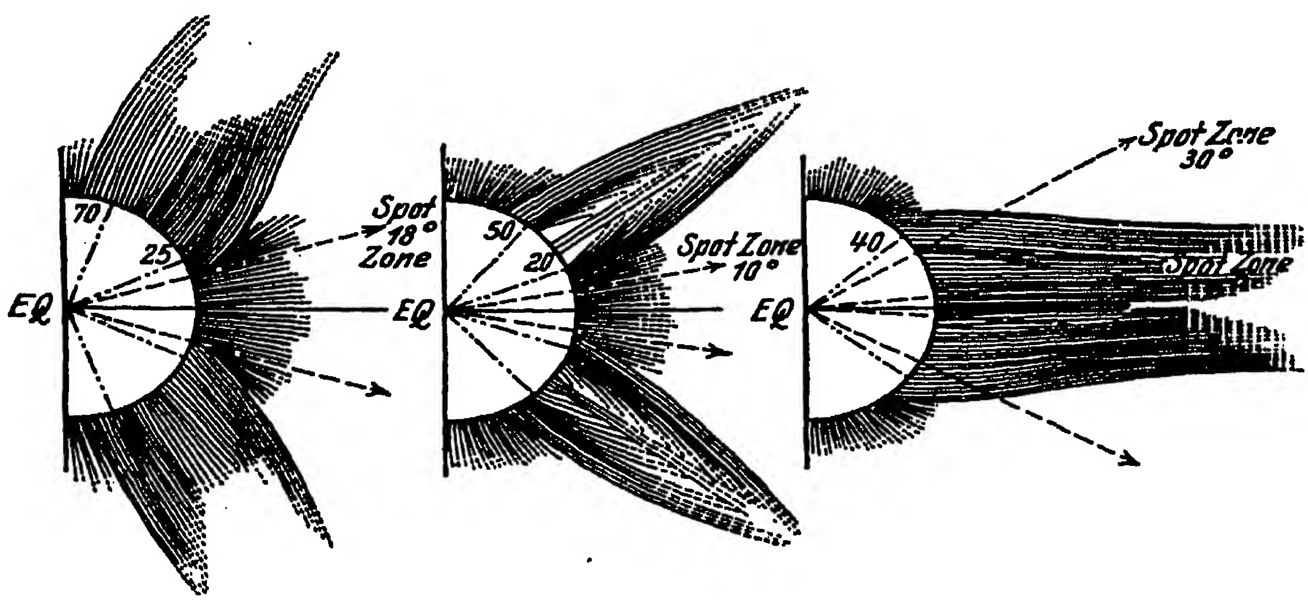

FIG. 127. Types of solar corona: polar, intermediate, equatorial, according to Lockyer.

epoch of the spots and prominences. Remembering what has been said about the migration of prominences (page 153), it must be concluded that the general appearance of the corona is closely associated with the distribution of prominences around the solar globe and follows the vicissitudes thereof, shifting with them at the various latitudes during the different phases of the eleven-year cycle.

The photometry and spectro-photometry of the corona, viz., the intensity of the light it radiates in its various parts, have been investigated during total eclipses by increasingly precise methods. Particularly from the observations made in Mexico during the eclipse of September 10, 1923, Ludendorff comes to the conclusion that the luminosity of the corona is due to the sun's own light, which is also confirmed by observations

of the polarization of the corona. The light of the incandescent gases of which it is composed is but a small part of the total light emitted.

Remarkable results were obtained in Takangon (Sumatra) by the expedition of the Potsdam Observatory, during the eclipse of May 9, 1929, and by the Italian mission during the one of June 19, 1936. Isophotes of the corona were derived from the various photographs by means of photometric measurements. The intensity of the corona seems to diminish in the ratio of the square of the distance from the solar limb; the colour and hence the temperature seem variable from point to point. The streamers do not alter considerably (as a rule not more than one stellar magnitude) the intensity from one point to the other of the corona. The corona is lower at the poles, where the intensity is about three times less than at the equator. It must be remarked, however, that the characteristics and intensity distribution of the corona in its different parts are not yet well known, either because of the difficulty of measuring by accurate processes or, as is probable, because of the inherent variability of the phenomenon.

Although the study of the coronal spectrum was commenced with the very first eclipse, immediately after the application of spectroscopic analysis for studying the sun and stars, the first reliable records were not collected until the eclipse of 1893, when Fowler, with a prismatic camera, succeeded in photographing nine monochromatic rings, whilst Deslandres photographed six rings in the violet and ultraviolet.

In the eclipse of 1898, the first in which the spectrum was obtained with a fair dispersion, astronomers could recognize fourteen lines, among which were those of unknown origin attributed to the element "coronium."

In the publications of the Lick Observatory, Campbell and Moore give a list of the wavelengths of the more definite coronal lines; they cannot be very precise, for even at the position of the most intense line (that of coronium in the green) there are considerable discrepancies in the results found by different observers.

In view of the apparent simplicity of the coronal spectrum it was believed that its interpretation in terms of series relation-

ships would be easy, and hypotheses have actually been propounded regarding the nature of the element that might produce this spectrum. But subsequent researches and increased knowledge of atomic structure and of the manner in which the line spectra are produced, have now permitted interpretations which seem more justified.

Bowen, studying the so-called "nebulium," viz. the emission lines visible in nebulae, propounds the hypothesis that they must be produced by some of the elements *H*, *He*, *C*, *N*, and *O* which exist in nebulae. It seems probable that on account of the very low density of nebulae, an emission may take place

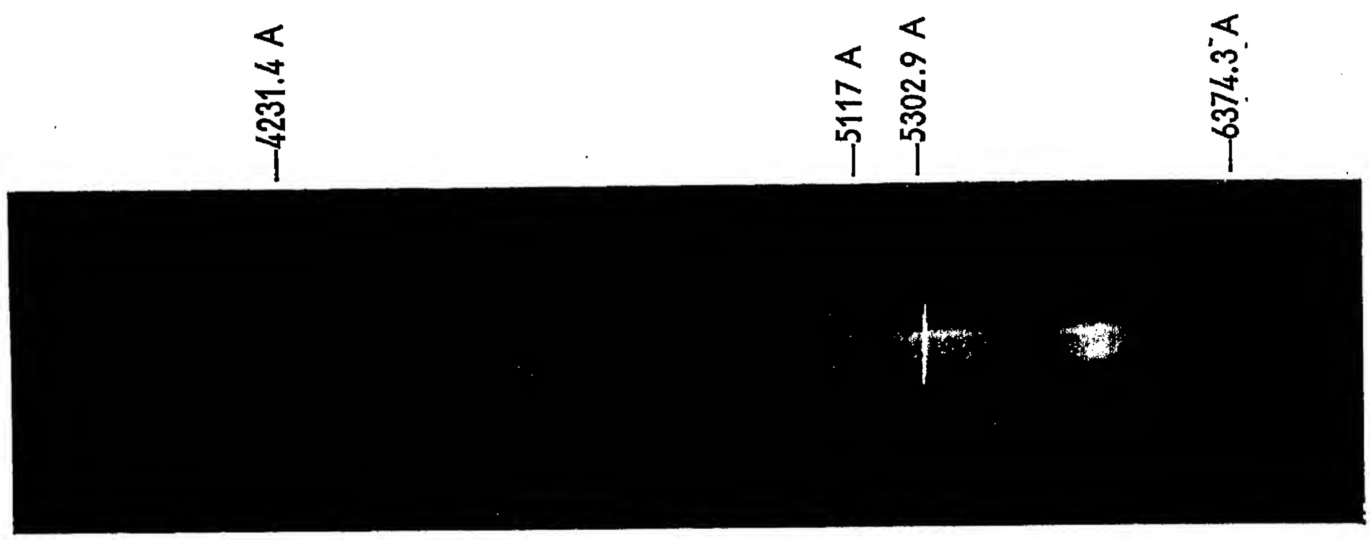

FIG. 128. Spectrum of the corona in the visible region. (Eclipse of June 19, 1936. Italian Mission at Sara.)

for an electronic transition from a metastable state. These transitions, usually forbidden under the conditions generally reigning in terrestrial laboratories, may well occur in celestial "laboratories," where the low density permits long free mean paths. Since *C* I, *N* I, *N* II, *O* I, *O* II, and *O* III are the only ions that may be present in nebulae in a metastable state and may produce lines in the region of the visible spectrum, they may be easily identified.

Eight of the most intense nebular lines have been classified by Bowen as being due to electron transition caused by metastable conditions in ionized atoms *N* II, *O* II, *O* III. Several of the faintest lines have been identified as belonging to highly ionized oxygen and nitrogen.

Similar conditions may be found in the corona, but

we may ask ourselves how it is possible for an atom to radiate these lines of its spectrum which are not produced under normal laboratory conditions, whereas it does not snow those which are already known from terrestrial experiments. Eddington is of the opinion that, besides the long free path permitted by the very low density of nebulae, there is another requisite, viz. that the exciting radiation be so faint that the atom has no great probability of absorbing to any extent during the whole duration of the metastable condition. He comes to the conclusion that the spectrum of the coronium is not due to forbidden lines. It is true that the density of the corona may be rather low, but on the other hand the exciting radiation is very intense.

In the most recent eclipses from 1918 to 1936, our knowledge of the coronal spectrum considerably increased, also as regards the red region, and it has been possible to effect increasingly accurate measurements of the wavelengths of its lines. In the eclipse of 1930 observed by Mitchell on the islet of Niuafoou in the Pacific, this observer discovered a new line in the extreme red. The wavelengths and mean intensities of the emission lines of the so-called coronium as concluded by him on the strength of the principal observations concerned are as follows:

Wavelength	*Mean intensity*	*Wavelength*	*Mean intensity*
3328·00	8	4359·00	4
3387·96	20	4567·00	4
3454·13	8	4586·00	2
3600·97	10	5117·00	2
3642·87	3	5302·91	20
3800·77	3	5536·00	1
3986·88	8	6374·28	12
4086·29	6	6704·00	2
4231·40	8	6776·00	8
4311·00	2		

One of the most notable and most intense of these lines is 5303 A, which has long been known, but it has not been possible to identify the origin either of this line or of the others. To the lines stated in the table is to be added, according to Righini, the line 5354·2 A, which has hitherto been omitted, it being

believed to be of chromospheric origin; this line, in fact, almost coincides with a titanium line of the chromosphere, but, from the spectrograms obtained by the Italian mission during the eclipse of June 19, 1936, which were taken by pointing the slit of the spectrograph at about one minute of arc from the solar limb, so as to completely exclude the chromosphere, it appears that this line also belongs to the corona.

In the infra-red the spectrum was examined by Lyot by his own method (page 224) in full sunlight. The following table gives the wavelengths of the lines photographed by him and their intensities, expressed in millionths of that of 1 A of the continuous solar spectrum in their vicinity:

Wavelength	*I*
7059·62A	4
7891·94A	29
8024·21A	1·3
10746·80A	240
10797·95A	150

The last two lines are particularly intense, and the first was observed by Lyot up to four minutes of arc, the second up to two and a half minutes from the solar limb.

From the spectra of the corona obtained during the eclipse of May 9, 1929, Grotrian finds that, as a rule, the intensity of the emission lines is proportional to that of the continuous spectrum. He further finds, by precise photometric measurements, that for the three best known lines the intensity ratios are as follows:

$$6374\ \text{A} : 5303\ \text{A} : 3388\ \text{A} = 1 : 12 : 2,$$

and that the energy emitted by the principal emission lines is only 1/160 of their total radiation, so that the colour of the corona is not greatly influenced by the radiation of the green line.

Mitchell observes that, judging from the structural details visible in the lines 5303 A and 6374 A, it is not probable that they originate from the same atom, or at any rate, not from the same atom in the same state of ionization. Now the first line (5303 A) is the familiar "green line" of the corona in the

same region as the analogous lines observed in the spectra of nebulae which, as already stated, have been identified by Bowen, and in the same region as those in the spectrum of the polar aurorae. According to measurements by Hopfield, the second line mentioned (6374 A) might be a line belonging to neutral oxygen, which would confirm the theoretical views of Eddington. The new line discovered by Mitchell in the eclipse of 1930 is the 6776·00A.

These emission lines and the other lines of the coronal

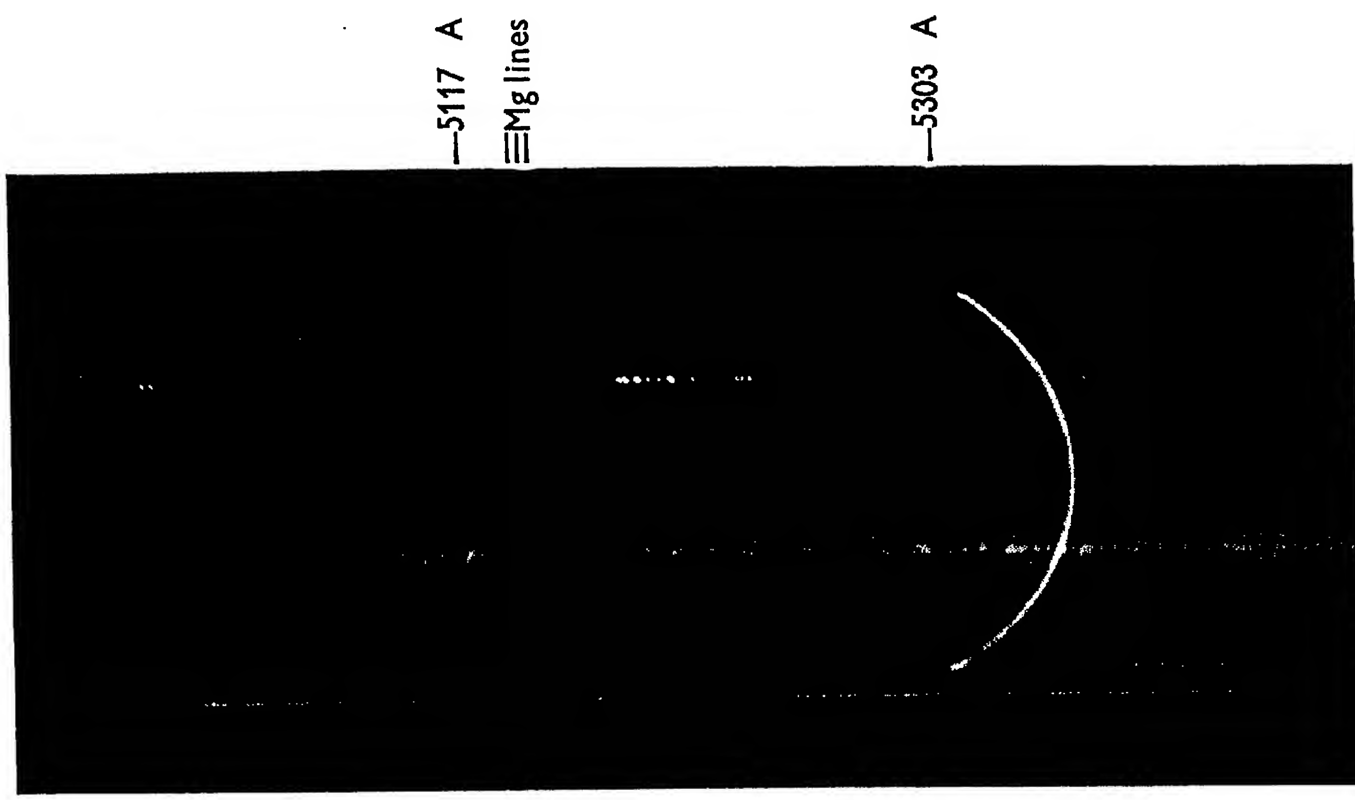

Fig. 129. Corona emission lines 5117 A and 5303 A photographed in full sunlight by Lyot. (The short emission lines are due to prominences.)

spectrum occur only in the inner corona and extend to 5′, i.e. up to 200,000 km from the sun's limb; in the middle corona, on the other hand, there is a continuous spectrum, and in the outer corona the Fraunhofer lines are faintly visible. The line 5303 A is less intense in the neighbourhood of the solar axis and is at maximum intensity in the regions near the prominences.

Besides the variations in shape of the corona with solar cycle, it seems that there is a variation in the intensity of the emission lines of coronium.

The corona, especially in its outermost parts, often presents

a continuous spectrum with the Fraunhofer lines: it is this that is responsible for practically the whole luminous intensity of the corona. This spectrum is due to the solar light being diffused by the corpuscles of which it is composed. The light of the outer corona certainly presents the characteristics of light diffused by the molecules in a gas. These characteristics

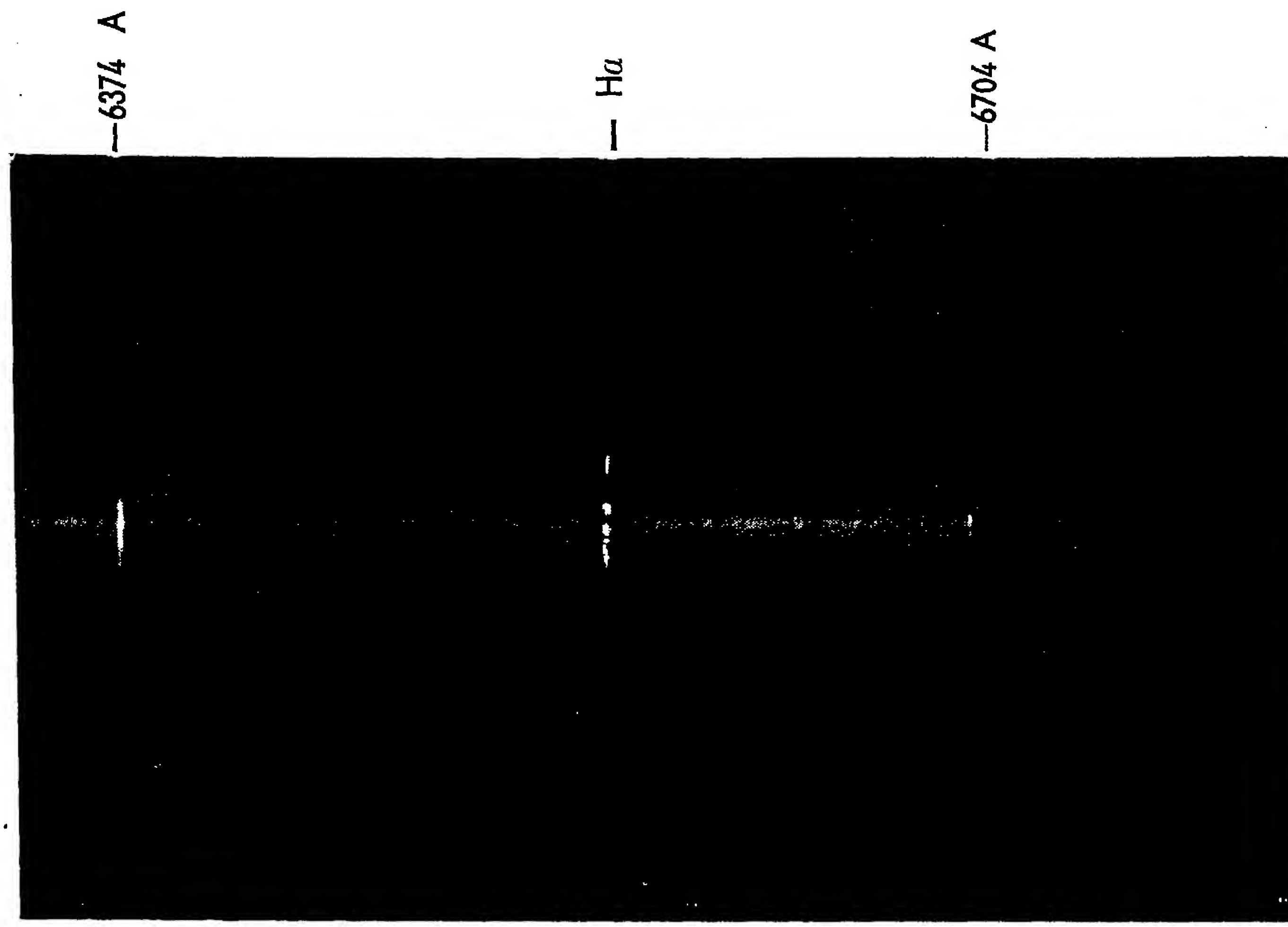

Fig. 130. Corona emission lines photographed in full sunlight by Lyot at 40″ from the east limb. (August 30, 1935.)

are: the partial polarization which is observed in the light of the corona, and the colour of its outermost parts, which shows an absence of radiations of large wavelength, in accordance with the fact that the quantity of light diffused by a gas is proportional to the inverse fourth power of the wavelength (Rayleigh scattering).

The hypothesis that the continuous spectrum is due to dispersion of the sun's light by free electrons has been confirmed by observations effected by Ludendorff in the eclipse of September 10, 1923, he having found that the intensity dis-

tribution of the continuous spectrum in the region 3820 A to 4840 A is identical with that of the solar spectrum.

The position of the Fraunhofer lines of the outer corona has been compared with the position occupied by these lines in the spectrum of diffused skylight; in this way a slight shift towards the red has been detected both at the east and at the west of the sun; this has led to the hypothesis that the diffused material of the corona has a radial recession from the sun of about 26 km/sec, viz. of the same order of magnitude as has been found in the motion of the details of the inner corona.

It may be said in conclusion that the coronal spectrum has on the whole been studied but little and is still little known even from the results obtained at each new eclipse. However, thanks to the possibility of observation in full sunlight in accordance with the recent experiments to which we have referred, observers may very soon succeed in defining the nature and condition of the gases constituting the corona. At any rate, from what we have said it is certain that its density must be extremely small, as is also obvious from the fact that many comets (which are themselves bodies of low density) have passed through the corona at a velocity of more than 500 km/sec without undergoing the slightest observable resistance in their movements; such was the case, for example, with the comet of 1843, which came within a distance of 160,000 km from the sun's surface.

CHAPTER V

PHYSICAL CONSTITUTION OF THE SUN

Theory of Ionization

We have seen (page 98) how the changes observed in the spectrum at different levels of the sun's surface depend on the greater or smaller proportion of ionized atoms at each particular level. The process of ionization whereby an atom liberates one or more electrons, is a phenomenon analogous to chemical dissociation in which a gaseous molecule splits up into two molecules that are also gaseous. It is known how this dissociation is facilitated by decrease of pressure; hence the increase of ionized atoms and the appearance of the spark spectrum when we pass from the lower layers of the solar atmosphere to higher ones in which the pressure is necessarily smaller.

The idea of considering ionization as actual dissociation and applying to it the traditional rules of physical chemistry, originated from the Indian physicist Megh Nad Saha. He conceived this idea in 1921, deriving from his theory a formula which is now extensively and successfully used for interpreting the spectra of the photosphere, the chromosphere, and the stars in general. We will state briefly what Saha's theory consists of and what conclusions are to be drawn from it.

The reversible dissociation of a gas *A*, whereby a molecule of gas *A* splits up into a molecule of gas *B* and into another of gas *C*, is indicated by the relationship:

$$\mathrm{A} \rightleftarrows \mathrm{B} + \mathrm{C}.$$

In the same way, when considering an atom of an element (such as, for example, calcium) when ionized, we may formulate thus:

$$Ca\ \mathrm{I} \rightleftarrows Ca\ \mathrm{II} + e,$$

where *Ca* I indicates the neutral atom, *Ca* II the once-ionized atom, and *e* the electron.

The laws of physical chemistry enable us to establish the degree of dissociation, viz. the proportion of ionized atoms as a function of the temperature T and of the pressure P, provided that the energy absorbed in the process of dissociation is known. This energy is generally known, as it is simply the ionization potential (measured in volts) of (in our case) the calcium atom. Saha's formula simply links up these quantities and thus permits calculation of the percentage of ionized atoms of each element when we know the ionization potential, temperature and pressure.

Vice versa, if from the presence of certain lines in the spectrum we can deduce the percentage of ionized atoms and we know the ionization potential, we shall be able, for a given series of temperatures that are possible in the stellar atmosphere, to calculate the corresponding pressures or, conversely, the pressures being given, to calculate the temperatures.

Hence, for instance in the case of calcium, which has an ionization potential of 6·1 volts, we calculate by Saha's formula the following table in which the pressure is expressed in atmospheres and the temperatures in degrees absolute:

PERCENTAGE IONIZATION OF CALCIUM

$\frac{P}{T}$	10	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-6}
4000°	—	—	—	3	9	26	93
5000	—	2	6	20	55	90	—
6000	2	8	26	64	93	99	
7000	7	23	68	91	99	—	
8000	16	46	84	98	—		
9000	29	70	95	—			
10000	46	85	98	complete ionization			
11000	63	93	—				
12000	76	96					

Saha's formula says that the percentage of ionization increases:

(*a*) with increasing temperature;
(*b*) with decreasing pressure;
(*c*) with decreasing ionization potential.

Calcium has a rather low ionization potential, and it is interesting to compare the foregoing table with the one following, calculated for atomic hydrogen, which has an ionization potential of $13 \cdot 5$ volts. At the temperatures indicated in the table the dissociation $H_2 \rightarrow 2H$ is complete, so that it is not necessary to consider the molecule.

PERCENTAGE IONIZATION OF HYDROGEN

$\frac{P}{T}$	1	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-6}
7000°	—	—	—	1	4	12
8000	—	—	2	5	18	50
9000	—	2	6	20	63	90
10000	2	6	17	49	87	99
12000	9	28	68	94	—	—
14000	27	65	93	—		
16000	55	90	—			
18000	80	97		complete ionization		
20000	92	—				

From comparison of the two tables it may be inferred that very much higher temperatures are required to produce a given percentage ionization in hydrogen than are required in the case of calcium. Caesium, which has the lowest ionization potential of all elements known hitherto, should be entirely ionized at about 4000° and 10^{-4} atmospheres, whilst at the same pressure a temperature of about 20,000° is necessary for completely ionizing helium, which has the highest potential ($24 \cdot 4$ volts) of all known elements.

This and other consequences of Saha's theory are applied for the interpretation of the solar spectrum. We have already said that in the reversing layer and in the chromosphere there are relatively small pressures with temperatures of from 6000° to 7000°, so that we find, for example, calcium atoms both in the neutral and in the ionized state. This explains the simultaneous presence of the line 4227 A of *Ca* I and of the lines H and K of *Ca* II. At increasing heights the pressure will decrease, whilst the temperature, on the hypothesis of equilibrium of radiation, will not, according to Milne's calculations,

drop below 5000°. Under these conditions the percentage ionization of calcium must be complete or almost complete, and hence only the enhanced lines should be emitted from the highest parts of the chromosphere. It has been established that the H and K lines extend up to 14,000 km above the level of the photosphere, whilst the line 4227 A is visible only up to an altitude of 5000 km; this may be explained by the fact (anticipated by theory) that above 5000 km calcium is completely ionized.

The ionization potentials of strontium (5·7 volts) and barium (5·1 volts) being lower than those of calcium, should be attained at higher pressures for a given temperature, and indeed, in the spectrum of the reversing layer the normal lines of these elements disappear much sooner.

From similar observations it has been possible to estimate the distribution of pressure in the various solar envelopes. At pressures below 10^{-3} atmospheres, sodium (ionization potential 5·1 volts) is completely ionized, so that in the chromosphere the D lines, which are normal lines of the main series, only attain an altitude of 1200 km. Below 10^{-1} atmospheres, potassium (ionization potential 4·3 volts) should be completely ionized at 7000° and below 10^{-3} atmospheres at 500°; hence in the chromosphere and in the reversing layers there will be few neutral atoms. Since, however, the lines of ionized potassium are not in the visible region of the spectrum, potassium will not be visible even when present in large quantities. The same can be said of rubidium and calcium, whose ionization potentials are very much lower.

The ionization potential of magnesium is higher than that of other alkaline earths, and hence the lines of the normal atom should be visible at relatively high altitudes; Mitchell found the triplet 3838 A, 3832 A, 3826 A, up to a height of 7,000 km. At the same time we should also find a considerable density of ionized atoms. On the other hand, the well-known line 4481 A only attains a low latitude, which at first sight seems anomalous. But Fowler has proved that it belongs to the fundamental series, and however easy its production may be it must in any case be more difficult to excite than any of the enhanced lines of the other series, which unfortunately are outside the accessible interval.

Saha's formula also says that in the photosphere molecular hydrogen must be dissociated into atoms; this conclusion seemed accurate from the point of view of spectroscopic observation, because, in the solar spectrum, lines pertaining to the so-called "secondary spectrum" of hydrogen had never been identified. The presence of various chemical compounds, and particularly of hydrides, had not been considered as being in opposition to the hypothesis of complete dissociation. Moreover, assuming the total pressure to be equal to one atmosphere, the dissociation of the molecule H_2 proved complete, not only in the photosphere where the temperature is about 5000°, but also in sunspots where the temperature drops to 4000°.

On the other hand, taking as basis the experimental researches of Langmuir on the equilibrium $H_2 \rightleftarrows 2H$, Piccardi proves that the percentage of molecular hydrogen present in sunspots may vary from 7 to 0·01 per cent of the total quantity of hydrogen, according to the level, and is about 0·8 per cent in the reversing layer. In view of the extraordinary abundance of hydrogen and the tremendous thicknesses of the solar atmosphere, one might be inclined to think that molecular hydrogen would be observable even if present in such slight concentration. A relative abundance of the order of one-thousandth that of hydrogen is already sufficient to constitute on the sun a very great abundance—greater than that of almost all other elements.

The failure to identify the lines of the secondary spectrum of hydrogen in the solar spectrum was probably attributable to the complication of the band spectra, often overlapping and each consisting of very few lines. In view of the foregoing considerations Piccardi, making an exact examination of the so-called "Fulcher bands" belonging to the molecule H_2, which are of fairly high density, succeeded in establishing their probable presence on some spectrograms of spots taken at the Arcetri solar tower, and on the chart of sunspot spectra prepared with great dispersion at the Mount Wilson Observatory. The presence of the molecule H_2, to be anticipated on the ground of chemico-physical and thermodynamic considerations, thus seemed at all events to be very probable if not a demonstrated fact, contrary to the consequences of Saha's theory. It must be mentioned that, according to

recent researches by Richardson on Mount Wilson plates, there seems to be no evidence for lines of H_2 on the photosphere.

In view of the importance which hydrogen possesses in relation to the composition of the stellar atmosphere, Russell subjected the problem to a fresh examination, basing himself upon the number and intensity of the lines identified by Piccardi, and calculating that the relative intensity of the Balmer lines of atomic hydrogen and of the lines of the molecule is in accordance with the degree of dissociation deduced thermodynamically.

Moreover, Russell was able to deduce from the intensity of the identified molecular lines that hydrogen, as we shall see (page 271), must be even more abundant in the solar atmosphere than is generally acknowledged, as compared with the other elements. The problem of identification of the bands is, however, extremely difficult, and even the presence of several hundred lines attributable to the secondary spectrum would not, strictly speaking, demonstrate with certainty the presence of the molecule H_2 unless there were chemico-physical considerations to confirm this idea. Bearing further in mind that the bands identified according to theory are formed only with a strong excitation potential, it must be acknowledged that for the moment this question remains undecided.

On the other hand, because of the high ionization potential of the helium atom, ionization can at no place be complete. So helium will hardly be ionized at all in the solar atmosphere; there will only be lines of the neutral helium atom in the Fraunhofer spectrum, and their presence in the spectrum of the reversing layer cannot be deduced from the considerations set forth hitherto, but Saha shows how the lines that are generally considered as belonging to helium do not belong to the main series, which is situated in the ultra-violet and hence will not be absorbed unless a sufficient portion of the atoms possesses a considerable excitation.

The theories of ionization and excitation of atoms account sufficiently well, as we have seen, for the distribution in the solar atmosphere of the levels of production of different lines of the same element, and make known to us the distribution of temperature and pressure as well as the composition of the

various solar envelopes. These numerical valuations must still be considered as provisional, since the calculation made for an isolated element must be corrected to allow for the complexity of the solar atmosphere; but it may certainly be affirmed that Saha's theory has paved the way for ascertaining precisely the number and distribution of atoms in the sun. Moreover, it may be said that this theory, after Kirchhoff's, constitutes one of the most noteworthy advancements in astrophysics.

In order to arrive at a more precise valuation of Saha's theory Russell extended it to the mixture of two or more elements, arriving at the conclusion that the ratio of the number of ionized atoms to that of the non-ionized atoms, for any two given elements in a gaseous mixture, yields a fixed proportion of the one to the other which depends only on temperature and is independent of pressure, of the relative abundance of the two elements or of the presence of other elements. These latter conditions affect the increase of ionization without altering this proportion. The element with the lowest ionization potential is always the most highly ionized one. Russell further considers the ionization of elements of a higher order than the first and finds that only two successive ionization layers may be present at the same time in considerable proportions.

As a consequence of the ionization theory and in connection with what has already been stated (page 182) regarding the distribution and movements of the photosphere and chromosphere, we may also state how, according to Russell and Stewart, the chromosphere, the reversing layer and the photosphere can be imagined to be distributed and limited around the solar globe.

In the highest envelope, in contact with the corona, there is a deep layer, the chromosphere, in which gases are sustained by radiation pressure acting upon the individual atoms. The pressure and density in this layer slowly increase in a downward direction (when gravity begins to overcome the radiation pressure), and the pressure at its base may be of the order of 10^{-7} atmospheres. Below this level gravity is predominant in the equilibrium, and the pressure increases rapidly with depth, whilst the temperature remains almost constant and not far

from 5000° until the gases are transparent. This region is the one described as the "reversing layer."

The division between the reversing layer and the chromosphere would thus be the level at which the ionization of the first degree is practically complete, viz. the upper level of neutral calcium. This, as we have seen (page 172), approximately corresponds to the level at which the movements of the absorbing vapours around sunspots change from efflux to influx, and implies a definite physical state of the chromosphere, viz. the complete ionization of metallic vapours.

When the pressure reaches 10^{-2} atmospheres the general absorption begins to render the gas opaque. This opacity increases considerably with the pressure and, with a rather rapid transition, the reversing layer changes into the photosphere which, with our means of observation, resembles an opaque mass. As soon as opacity becomes considerable the temperature increases in accordance with the theory of radiative equilibrium as developed by Schwarzschild and Eddington. The actual photospheric temperature (page 317) observed represents a mean value for the layers from which the radiation is emitted towards the earth.

Composition of the Sun

We have already stated (page 93) how, of the ninety chemical elements known, about sixty-two have been more or less definitely identified in the solar spectrum. Of the remaining twenty-eight, twelve have lines so unfavourably situated in the spectrum that we cannot hope to discover them unless the researches are extended as far as possible towards the ultra-violet and infra-red as has recently been done, for example, in the case of phosphorus; for another twelve elements the spectra have not yet been studied with such precision as to permit of certain identification. There thus remain four elements: osmium, rhenium, bismuth and radium, for which the most intense lines are in the accessible regions of the spectrum and do not appear in the solar spectrum. Probably these metals are present only in small quantities, if they exist in the solar atmosphere. Rhenium is very rare on the earth, whilst radium, on account of its short life, must be rare every-

where in the universe, so that we cannot expect to find this or any of the other highly radio-active elements in considerable quantities.

In addition to elements in the atomic state, we also find in the photosphere or in sunspots, as already stated, the hydrides CH, NH, OH, MgH, AlH, SiH, CaH, the oxides AlO, TiO, ZrO, BO, the carbon compounds CN and C_2, silicon fluoride SiF, and probably also molecular hydrogen H_2. It is probable that a few other molecules commonly met with, such as CO and N_2, exist in the solar atmosphere, but these in their normal state only absorb in the extreme ultra-violet and hence cannot be identified. It is known that the hydrides are dissociated fairly easily, and their presence is another proof of the large quantity of hydrogen in the sun. Of the other compounds discovered hitherto, it is known that at least one of the constituents is very plentiful on the sun.

All this tells us about the qualitative composition of the sun or at least of its outer layers. Interesting considerations on the quantitative composition have been made by Russell.

It must be remembered that the sun has not a well-defined surface. In the highest part its atmosphere becomes dissipated into space like that of the earth, but towards the inner layers there is no solid surface; the gas gradually becomes more nebulous, so that we can only observe relatively thin layers. This increasing opacity is due to the presence of electron and ion gas as has been demonstrated by Stewart and later by Milne. Milne's calculations indicate that the variation from a very low density to opacity takes place in a layer of hardly 30 km thickness, which explains the sharp definition of the sun's edge as seen even in the largest telescopes. The greatest part of the absorption producing the Fraunhofer lines takes place in this thin reversing layer, with an incredibly small quantity of material for the various elements.

Lockyer already showed, more than forty years ago, by direct comparison with the flame of a Bunsen burner containing a small quantity of common salt, that in this flame the sodium lines appeared more intense than those of the solar atmosphere. Modern atomic physics confirm this fact and enable us to calculate from the breadth of an absorption line produced in a rarefied gas, the number of active atoms in the production

of that given line which are existent in a given unit of air in the absorbing layer, whatever be its thickness.

The most intense solar lines are sufficiently broad to permit measurement of their profile, this usually being effected by means of a microphotometer which brings into evidence from spectrograms, by means of a thermo-electric pile or a photo-electric cell, the variation of intensity through the line compared with that of the continuous spectrum. Hence we can determine the number of atoms in a given unit of area above

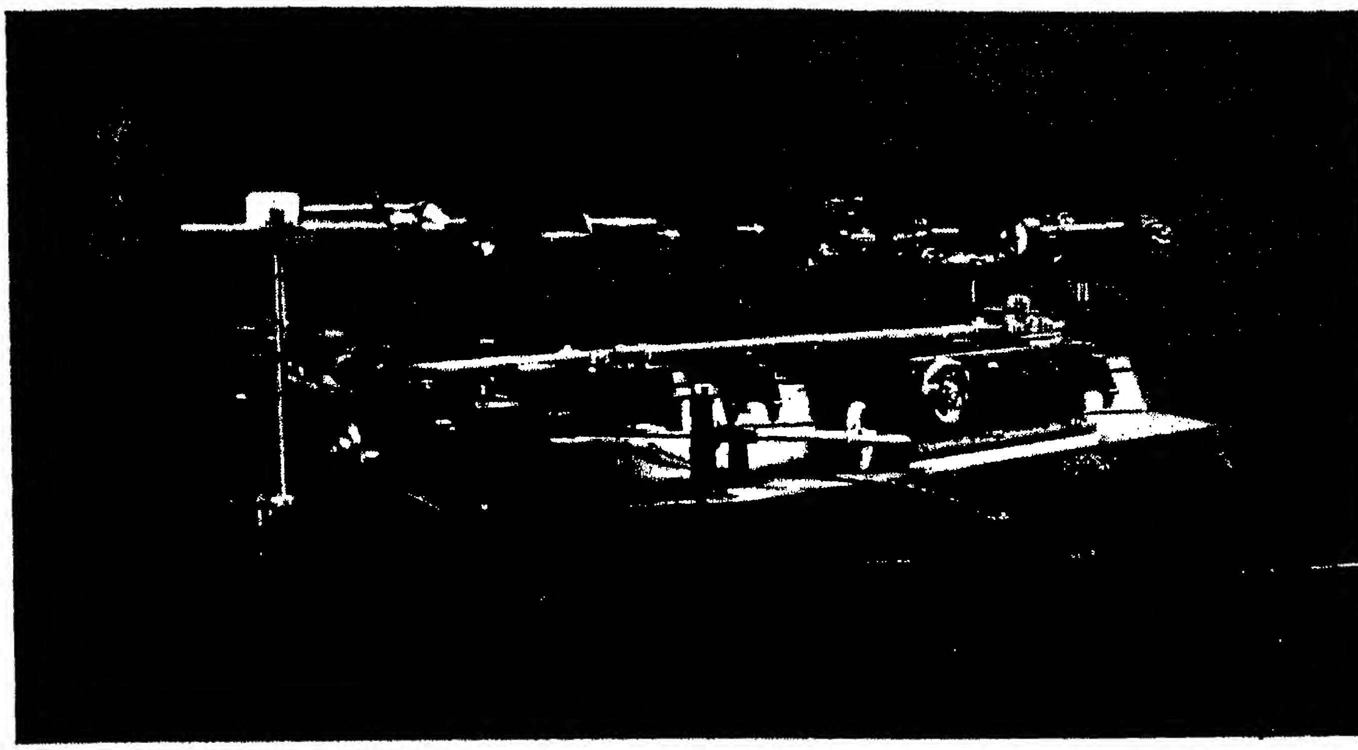

FIG. 131. Recording microphotometer of R. Observatory at Arcetri.

the photosphere, and it is found, for instance, for the most intense lines (viz. for the H and K lines of *Ca*II taken together) that they amount to 2×10^{19} atoms per square centimetre, which number is equivalent to that of the molecules existing in a layer of ordinary air about 8 mm thick. For sodium lines the corresponding number is nine hundred times smaller, thus confirming Lockyer's experimental conclusion.

For the thousands of fainter lines, the measurements would be too uncertain, because the measured breadths depend on various factors: solar, atmospherical and instrumental; the difficulty may, however, be overcome in another manner by availing ourselves of modern theories on the origin and formation of the spectra.

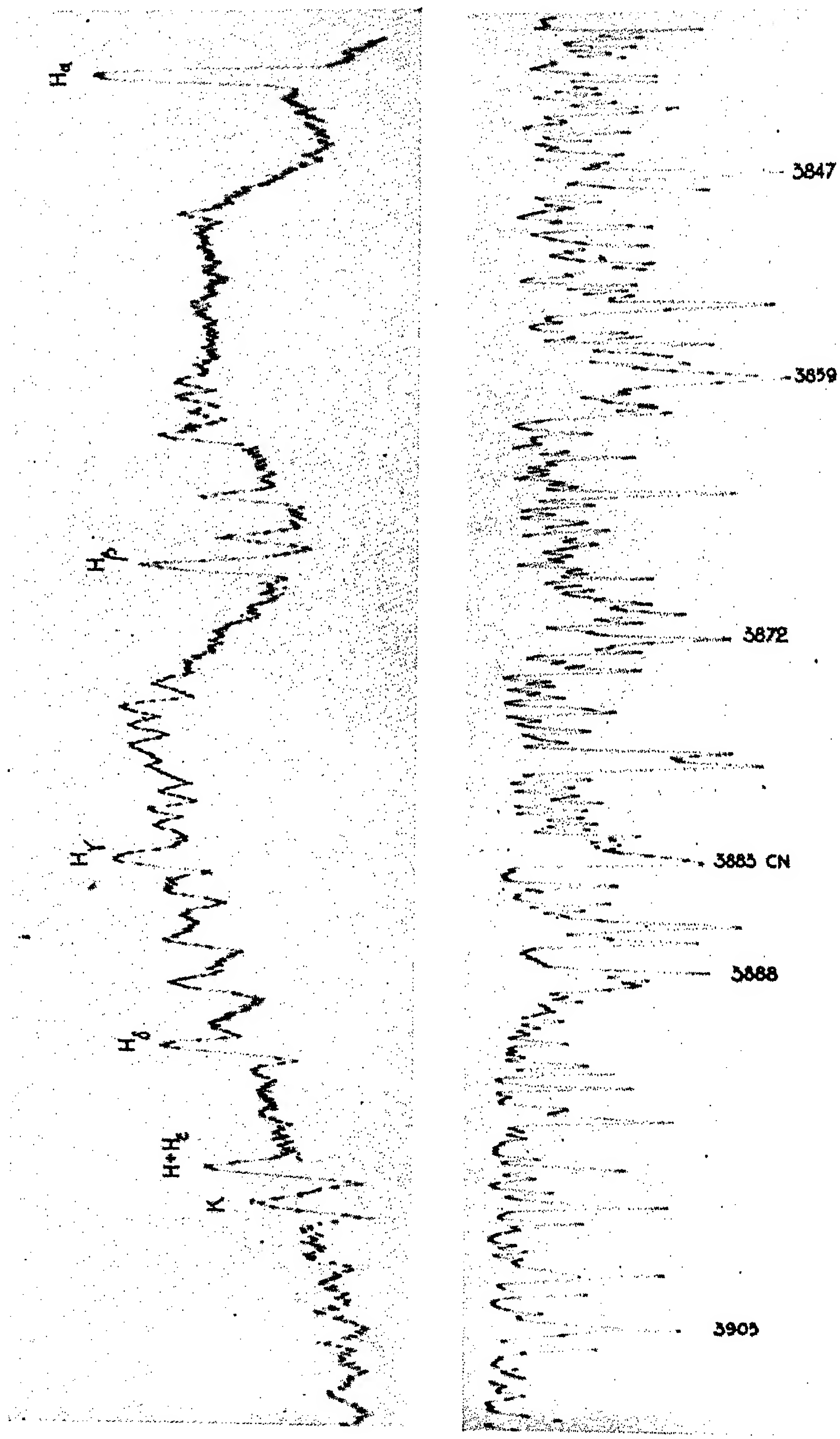

Fig. 132. Examples of microphotograms taken with the microphotometer (Fig. 131).

Top: Spectrum of the star *Nova Herculis 1934* with emission lines (transmission ratio of plate to diagram 1 : 13).
Bottom: Solar spectrum from 3847 A to 3905 A with Fraunhofer lines (compare with Fig. 38; transmission ratio 1 : 7).

There may, for example, be two lines in the same multiplet, the most intense of which has the intensity 4 in Rowland's empirical scale and the faintest the intensity 1; theory tells us that, in order to produce the first (i.e. the most intense), forty times more atoms are required than for the second. Another pair of lines with the same Rowland intensities may give a theoretical ratio equal to 25, another to 50, and so on, for we know that Rowland's estimates are only approximate. But, since we have at our disposal a large number of lines, the average of them all gives a good determination of the relative number of atoms which produces lines of different intensities in Rowland's scale.

In this way Russell, Adams and Moore were able to calibrate Rowland's scale, and with the knowledge of the most intense lines which have been measured individually, they ascertained the actual number of atoms that are excited in order to produce a solar line of a given intensity.

For a line of intensity zero in Rowland's scale, viz. a scarcely visible line in a spectrum obtained with considerable dispersion, one may calculate that there are 10^{13} active atoms per square centimetre, which would constitute a gas layer of a thickness of about $2 \cdot 5 \times 10^{-6}$ mm, and for the faintest lines of the scale a very much thinner layer.

Moreover, we can estimate how many atoms of each element are engaged in the production of the lines of that element which are observed in the solar atmosphere. In order to find the total number of these atoms it must be remembered that there are some which produce lines in the invisible parts of the spectrum, viz. the ultra-violet and the infra-red. This may be done if the important lines are visible which are absorbed in at least one of their states of energy, for then the number of atoms occurring in other states may be calculated by the thermodynamic theory when the sun's temperature is known. In this way the number of neutral atoms can be deduced for many elements.

Most of the ionized atoms have their most important lines in the extreme ultra-violet, but the spectra of some of them are such that it is possible to calculate the number of ionized atoms.

We have already stated how one can calculate by Saha's

formula the percentage of ionized atoms when hypotheses are propounded as to the distribution of temperature and pressure in the solar atmosphere. At the level of the photosphere it is calculated that an element with an ionization potential of 8·5 volts must be half ionized and half neutral. The bulk of the metals have a lower ionization potential, so that, for instance, only one sodium atom out of a million is neutral, and one out of a hundred for calcium; a fifth of the iron atoms and one-third of the silicon ones are neutral, but when we come to zinc, which has a higher ionization potential, it is found that 85 per cent of its atoms are neutral, 99·6 per cent for carbon, whilst for hydrogen we find but one single ionized atom to thirty thousand neutral ones. By means of these data Russell arrives at a calculation for the total quantity of the various metals constituting the solar atmosphere.

Six elements, viz. sodium, magnesium, silicon, potassium, calcium and iron, give 95 per cent (in weight) of all the metallic vapours, and nine others almost the whole 5 per cent remaining, as is seen in the following table:

ABUNDANCE OF METALS IN THE SOLAR ATMOSPHERE
(GRAMS PER SQUARE METRE)

Magnesium	150	Manganese	4·0
Iron	100	Cobalt	2·5
Silicon	60	Chromium	2·5
Sodium	40	Titanium	0·8
Potassium	25	Vanadium	0·6
Calcium	20	Copper	0·6
Aluminium	6	Zinc	0·5
Nickel	6	All others	0·1

The abundance of an element is probably a function of as yet unknown properties of the structure of the atomic nucleus. The quantity of compounds present in the solar atmosphere is likewise very small, but it must be borne in mind that molecules have a great advantage in the nature of their spectrum of bands. The passage of one electron, which in an atom gives rise at the utmost to a small number of multiplets, produces in a molecule a complete system of bands with thousands of lines.

The relative abundance of the various elements, as is seen from the foregoing table, is about the same as on the earth.

The results of Clarke and Washington, deduced from hundreds of accurate analyses on typical rocks, indicate a large amount of silicon, aluminium and titanium. But these results represent the composition of the outer terrestrial crust up to a thickness of 15 km, which is pre-eminently composed of granite rocks that are richer in these three elements than the very much denser stratum of compact rock at greater depth. Moreover, nickel and cobalt are less abundant in terrestrial rocks than in the sun; but in meteorites, which are perhaps better representative of the general composition of the solar system than the external rock of the earth's crust, these elements are present in the same proportions as on the sun.

The quantity of "rare elements" is in general alike on the sun and earth. It is true that scandium seems to be more plentiful on the sun, but small quantities of this element dispersed in rocks may escape chemical analysis.

The quantities of non-metallic elements in the solar atmosphere are far more difficult to determine, because the lines available for examination only proceed from atoms in high states of excitation. For every atom in such a state there is a very large number of atoms in the normal state, perhaps millions, and these enormous factors are difficult to determine accurately. Russell, however, calculates that carbon, sulphur and nitrogen must be as abundant as the more common metals, oxygen still more so, and hydrogen far more abundant than all others. He concludes that at least 90 per cent of all the atoms in the solar atmosphere (perhaps 95 per cent or still more) are atoms of hydrogen. Of the remaining portion, helium and oxygen contribute two-thirds, whilst all the metals, together with carbon and sulphur, comprise the remainder. These are the proportions of the various constituents by volume of gas. As to weight, the metals, whose atoms are very much heavier, amount to perhaps a quarter of the total, perhaps less.

Hence the probable composition of the solar atmosphere may be assumed to be as shown in table on next page.

In the following (page 290) we will say a few words about the hypotheses that may be propounded regarding the constitution of the sun's interior; little can of course be said about its composition. Even if it is true that the great cyclonic

vortices which produce sunspots must originate from considerable depths, they are never more than a small fraction of the sun's total radius. At any rate it seems probable that the deepest layers are sufficiently agitated by the currents concerned to nullify the slight tendency of the heaviest atoms to gravitate towards the centre.

The considerable differences in the abundance of the various elements, as shown by the researches mentioned, still awaits explanation. It is natural to imagine that the very diverse elements have in some way or other been produced by a more simple primordial substance, perhaps by hydrogen. The most abundant elements would then be those which for some reason

Elements	*By volume*	*By weight*
	parts	
Hydrogen	60	60
Helium	2 ?	8 ?
Oxygen	2	32
Metals	1	32
Free electrons ..	0·8	0
Total ..	65·8	132

or other have been formed in large quantities, whilst the rarer ones have either had less chance of forming or greater ease of transmutation into other elements.

Terrestrial researches of atomic physics will undoubtedly be able before long to explain the phenomena observed on the sun in particular and on celestial bodies in general.

Equilibrium of the Chromosphere

The composition and distribution of elements in the chromosphere, as well as its equilibrium under the action of the various forces which must be present there, have given much work to theoretical astrophysicists. One might indeed think that above the reversing layer, where the most turbulent layers and the vertical ascending and descending regions end, the elements must be stratified according to their atomic weight, as is more or less the case in our own atmosphere.

But the presence of calcium, which has a much higher atomic weight than hydrogen, at a considerably higher altitude than the latter, has led one to think that at the level of the chromosphere there must be other forces than that of gravity, which forces must act differently for each of the various elements in the chromosphere.

Milne, who subjected this argument to extensive researches, has enunciated an interesting theory which seems to account in the best possible manner for the facts observed. The forces other than gravity are due to radiation pressure exercised upon the bodies which absorb or reflect the radiation concerned. When an atom absorbs a certain radiation, it also absorbs the momentum that the quantum possesses when emerging from the sun's surface, thus receiving a light-impulse directed outwards. In this way the atoms of the chromosphere remain suspended at a certain level above the sun's surface, sometimes falling slightly and then sometimes ascending under the light-impulse, like small pieces of paper that may be sustained or caused to ascend in the air under the action of the wind. Naturally, among all the atoms, those that can absorb large quantities of light in proportion to their weight will have the greatest chance of floating in the chromosphere.

We will now consider a particular atom in the sun's atmosphere and a particular frequency which the atom is able to absorb or emit. In the Fraunhofer spectrum we shall find an absorption line of that frequency, which will have a certain residual intensity. The atom will be subject to the force of gravity in a downward direction, and to the force due to radiation pressure in an upward direction, which force will be proportional to the residual intensity of the line. If this second force is less than the first, equilibrium will be maintained by the gradient of the gas pressure increasing towards the interior. Consequently, if the force due to radiation pressure exceeds that due to gravity, the atom will be expelled. The process of expulsion will be continued until a state of stability is reached in which the atoms are sustained at a high altitude by radiation pressure in equilibrium with gravity, and the density will be so low that the impacts and hence also the gradient of gas pressure are negligible.

There is reason to suppose that the highest gases observed

in the flash spectrum during eclipses are kept in equilibrium in this manner, and that what we call the chromosphere is simply an atmosphere of atoms entirely or almost entirely sustained by radiation pressure. In the state of stability this atmosphere will be in radiative equilibrium, but since radiation is limited to the spectral lines of the gases which compose it, Milne considered the ideal case of a gas that radiates and absorbs only one frequency. The radiative equilibrium is thus monochromatic; the theory applies to the intensity in the frequency of that radiation.

The case of the H and K lines of *Ca* II is particularly interesting. Ionized calcium possesses an excitation orbit slightly larger than its normal orbit, so that the electron may revolve between the two orbits without much danger of falling spontaneously. In the case of other elements, the first orbit is relatively much larger, the energy required to reach that orbit is not very much less than that necessary entirely to detach the electron, and it is not easy to obtain a continuous source of light capable of producing orbital jumps without losing an electron. The great difference between the excitation energy and the ionization energy of calcium is what enables it to live at a high level in the solar atmosphere. The mean time taken by an electron to pass from one orbit to another is one twenty-thousandth part of a second and, according to Milne's calculations, it remains in that orbit for about one hundred-thousandth part of a second before falling back into the nucleus. During this time the number of revolutions made by the electron in the larger orbit is of the order of one million.

The excitation of the ionized calcium atom takes place in the two particular wavelengths corresponding to the lines indicated as H and K in the Fraunhofer spectrum. These lines are not completely dark but have a certain residual intensity sufficient to maintain the ionized calcium atoms in suspension in spite of solar gravity; as soon as the outflowing light is so weakened that it can no longer sustain atoms, it emerges into space at that intensity limit. By measuring this residual intensity it has been found possible to calculate the constants of the calcium atom and the mean life of the atom in the excited condition.

The chromospheric equilibrium, as proved by the theoretical

researches of Milne and other investigators, is certainly very delicate, and the slightest deviation from precise conditions of equilibrium may have catastrophical consequences. Such unstable conditions may on the one hand cause the solar atmosphere to fall slowly on to the sun, as would be evidenced by the descending currents observed by St. John for all the lines of the high atmosphere (page 190); on the other hand, counterbalancing these currents there are local disturbances by which the gases are expelled at great velocity. These disturbances manifest themselves in the flocculi and prominences, which form continually in the higher layers of the solar atmosphere.

A more complete explanation of the complicated mechanism governing conditions in the solar atmosphere will be arrived at with the progress of experimental research conducted concurrently with theoretical research. Photometric study of the lines of the solar spectrum has, as it were, hardly commenced and will certainly give important results in this field together with a better knowledge of the general and local movements observed in calm or disturbed regions at the various levels of the solar atmosphere.

Outline of Theories on the Constitution of the Sun

From the study made hitherto of the very complicated phenomena observed on the sun it may be concluded that, notwithstanding the copious material assembled, the difficulties of explaining them by a general theory are numerous. Remembering that the phenomena observed refer only to the outer envelopes of the sun's surface, which are of relatively small depth, and that we cannot find out anything about its interior, it will be understood that the numerous theories propounded in the past are not calculated to depict the complicated mechanism animating the solar globe.

The hypothesis that was put forward in the old theories of a solid or liquid solar nucleus can hardly be reconciled with the value found for the mean density of the sun, which is only a quarter of the mean density of the earth. Up to the times of Secchi and Lockyer it was supposed that the sun consisted entirely of gas. Considering the sun as a gaseous sphere, the pressure and temperature must decrease from the

interior to the exterior; one would therefore expect the sun's disc to decrease gradually in brightness at the limb, to shade continuously into the dark sky. On the contrary, however, the edge of the sun is seen to be well defined, which proves that the gases must become opaque in the photosphere. Since, at the temperature of the sun's surface (about 6000°), all known substances are vaporized, it is not likely that there are any solid or liquid particles in suspension in the photosphere which might produce clouds or condensations as on the earth.

Direct observations have shown us that the solar gases become opaque at a few hundred kilometres in the interior of the photosphere, and according to modern theories it would seem that this happens because they are ionized to a high degree. By passing the charge of a powerful condenser through a fine metallic filament, Anderson proved that the filament, when exploding into a mass of gas at a very high temperature so as to contain no solid particles, emits a continuous spectrum crossed by absorption lines similar to the Fraunhofer spectrum, which are produced in the outer parts of the luminous gas but are opaque in the volume it occupies during the explosion. On account of the very high temperature the atoms are to a large extent ionized, as is proved by the presence of enhanced lines in the spectrum.

Theoretically, too, we come to the conclusion that the free electrons may render the solar atmosphere so foggy that it already appears opaque at the pressure of about 10^{-3} atmospheres. This accounts fairly well for the sun's outer envelopes, but the most difficult phenomena to explain are those due to equatorial acceleration of the various layers (page 166) and those due to the presence and periodicity of sunspots, eruptions, flocculi and prominences.

A large number of theories have been propounded to explain these phenomena, but it must be acknowledged that none of them are as yet adequate or exhaustive. We will state briefly the fundamental principles of some of them.

Wilsing is of the opinion that the sun's equatorial acceleration depends on its being in a state of transition between a nebula and a solidified globe. The sun would tend towards uniform rotation and would finally attain it when the relative

movements of the different parts of its mass have come to an end through the effect of internal friction. Probably these movements have already ceased in the sun's interior, though they still continue at or near its surface. However, these relative movements cease so gradually that very long epochs elapse before they completely vanish, and hence they will appear constant for comparatively short periods of one or two centuries.

Moreover, Wilsing tried to give reasons for the periodicity of solar activity, assuming that according to present laws there are in the rotating system mass displacements due to the effect of gradual cooling and to other causes, producing a shift of the axis of symmetry, so that the instantaneous axis of rotation will no longer coincide with the axis of symmetry as is necessary for maintaining rotation with a constant axis. The fluid masses will be forced to balance this disturbance of rotation and to make the two axes coincide once more, but this equilibrium will be retarded as a result of internal friction of the fluid and gaseous masses, so that the disturbance may become very pronounced. Only, however, when it is so powerful that the frictional resistance is overcome, will there be a mass displacement to restore equilibrium. The periodicity of this process might be the cause of the eleven-year cycle. This might also account for the comparatively rapid increase of sunspot frequency during the rise of solar activity.

Considerable progress in theoretical knowledge of the sun's constitution has been made by Emden as a result of his hydrodynamic researches on gaseous spheres, which are directly applicable to conditions on the solar globe.

The masses emitting radiation at the sun's surface become denser and hence must move towards the sun's interior. If the sun did not rotate it would mean that, for the supposed condition of equilibrium, these masses descend until they reach the sun's centre, from which they would expel a like quantity of material that would fill the space left vacant at the surface. This formation of currents is completely altered because of the sun's rotation. For reasons of symmetry the surfaces of equal pressure are surfaces of rotation; pressure forces intersect the sun's axis, and the sinking masses which have got colder must maintain their moment of rotation. When approaching the sun's axis these masses will rotate with increasing rapidity,

maintaining their internal heat, while the outgoing masses will always have a smaller rotational momentum and lag behind to an increasing extent.

It is thus clear that there are gas masses of different densities and velocities which may give rise to well-defined successive "surfaces of discontinuity." To these surfaces Emden ascribes the conditions for the formation of very extensive waves. These waves are constantly increasing in a direction parallel to the sun's axis, and in consequence of their accelerated motion they will break through and form an enormous vortex in which the equilibrium of the rotational moments and of the energy of the various layers will be established. This mixing process is discussed by Emden, who comes to the conclusion that the supposed surfaces of discontinuity must be such that, when passing over them, we move towards the exterior of the solar globe at the same time as we recede from the axis.

The conclusions to be drawn from this theory are in accordance with some of the facts observed. The layers of the sun's equatorial regions must possess greater angular velocities than those of the polar regions. As a matter of fact, if the sun did not rotate, the convection currents could be freely formed and would mix the mass at all depths; the sun would thus cool down, as was thought to be the case according to former theories.

The rotation does not alter those currents, which travel along the solar axis towards or from the poles. But the nearer we approach the equator the more the formation of convection currents is obstructed by the formation of Emden surfaces, and the less deeply these currents penetrate into the sun. These currents only form in the interior of each individual layer between two consecutive surfaces of discontinuity. Consequently the thermal losses are more difficult to recover at the equator than at the poles, and hence the sun's surface would be hotter in the polar than in the equatorial regions. An experimental confirmation of this result might be found in the fact that the chromosphere is ordinarily higher at the poles than at the equator (page 135).

The same considerations may account for the different angular velocities observed at the equator or at the poles of

the sun. The external parts of the sun are shrunk by cooling, and their angular velocity increases, so that they gain on the internal parts. The convection currents, which in the polar regions make their way undisturbed to greater depths, bring about equalization of the angular velocity. But the nearer we approach the equator, the more rapidly the currents are checked by the surfaces of discontinuity, and the more slowly the angular velocities increasing at the exterior are transmitted to the interior because of the continuous new formation and rolling of the surfaces. As a final result the layers of the solar surface must have greater angular velocities in the equatorial regions than in the polar regions.

According to Emden's theory the formation of sunspots might also be explained by the friction between the solar strata. Between the two contiguous layers there arise, as stated, vortex waves whose sense of rotation is the same as that of the sun. As in the cyclones of our own atmosphere, a decrease of pressure is produced, so that these waves generate suction in the axial direction. The initial causes of the spots would be simply these small local vortices, and there would thus be a depression of the photosphere when they are formed near the surface.

The photospheric substances drawn downwards by rotation tend to become engulfed in the depression that has been formed and give rise to an irregular crater. The more central gaseous masses taking the place of those which have sunk, generate prominences and faculae in the neighbourhood of sunspots. If vortices are formed near the surface, rotatory movements of opposite sense will manifest themselves in the spots in the two opposite hemispheres.

The shape of the surfaces of discontinuity shows that in the neighbourhood of the equator there must be a zone where spots cannot be formed; it is only in exceptional cases that a discontinuity surface can be asymmetrical and give rise to spots in those regions. Similarly, discontinuity surfaces do not readily occur at the poles, and it is only at great depths that the differences of linear velocity become so great as to produce vortices. So there will be an absence of sunspot formations, which consequently occur more copiously at the intermediate latitudes.

It must be mentioned, however, that this theory of Emden does not account for the formation of bipolar spots, which, as we have seen, are the most frequent of the eleven-year cycle. As regards the appearance of spots at high latitudes after a period of inactivity, and their shift towards the equator, it might be supposed that during the minimum period the surface layers are intensely cooled before approaching the centre, and the internal currents no longer contribute in the same measure towards the re-establishment of thermal equilibrium. Owing to the comparative tranquillity of the bulk, the surfaces of discontinuity can form more easily at great depths and high latitudes. The spots have a greater tendency to occupy these regions, but according as the activity of the sun increases, the unstable equilibrium of the masses cooling down at the surface will be more rapidly disturbed, and the less strongly heated masses will consequently submerge more rapidly, giving rise to stratification and to spots at increasingly low latitudes.

This theory of Emden, like other theories, does not take into account the magnetic fields in sunspots nor any other phenomena in connection with this discovery; in fact, these magnetic fields have created a new situation in regard to sunspot formation and to solar constitution in general.

We have already pointed out (page 216) that the hydrodynamic hypothesis is the one that most satisfactorily accounts for the movements and currents which develop in the disturbed regions of the sun's surface.

A notable attempt at applying hydrodynamic and thermodynamic principles was recently made by W. Bjerknes in order to explain the circulatory system that must be produced in the upper layers of a gaseous sphere like the sun, the formation of spots and their lower temperature, their appearance in cycles, the bipolar structure, and so on.

The attempt is all the more notable in as much as the majority of the phenomena observed can be accounted for by comparatively simple hypotheses whose development inspires confidence in their great importance for research on solar physics.

Since the origin of solar phenomena is the sun's radiation, it follows that the light and heat radiation will be responsible

for its entire dynamics and also for the possible expulsion of electrically charged corpuscles.

The upper layers of the photosphere will be subjected to cooling and hence the conditions of equilibrium will be disturbed. The heat thus lost by the photosphere is restored by the deeper layers as a result of internal radiation, convection and conduction. Internal radiation is probably the dominant factor, especially in the deep layers of very high temperature. But a sufficient percentage remains to form powerful convection currents whose magnitude increases near the surface where, on account of the lower temperature, internal radiation is less predominant. The sun's rotation tends to distribute the various phenomena in a general zone of symmetry around the axis of rotation.

Bjerknes acknowledges sunspots to be vortices without propounding any hypothesis on the origin of their magnetic fields, and he presumes that these magnetic fields are related to the vortex motion in such a manner that the magnetic polarity is reversed when the direction of the vortex motion is reversed. Thus, comparing sunspots with tropical cyclones on the earth, he demonstrates that where there is vortex motion, with horizontal currents of increasing intensity in an upward direction, there must be a nucleus of cooled gas at the centre of the vortex. As a matter of fact the vortex will produce a pumping effect and will cause the gas masses to ascend and to be cooled adiabatically in the process.

In this way Bjerknes arrives at a formula giving the temperature gradient from the centre of the vortex to the exterior, in terms of the increase of velocity of the current with altitude and the angular velocity of the vortex at its surface. Applying this formula to a spot considered as a vortex at the surface of the photosphere, it may be assumed that the vortex itself extends to a certain depth below its level, and that the vortex velocity from zero to that depth continues to increase as a linear function in an upward direction. From the formula it is found that the fall of temperature is proportional to the depression that has formed at the surface of the photosphere, so that a depression of no more than a tenth of the thickness of the layer will, when taking part in the vortex movement, be sufficient to produce a decrease of temperature of 1,100° C;

a greater depression would cause a still greater decrease of temperature.

The velocities required in order to produce a given depression are found to be of the order of those which are observed and which are possible under the conditions existing on the sun; indeed, for a vortex whose diameter is ten times its depth, the velocities required for producing a depression of one-tenth is found to be 5·5 km/sec at a distance of 10,000 km from the centre of the vortex, and 17·5 km/sec at a distance of 100,000 km. With greater decreases of temperature the velocities increase.

The theory of vortices thus explains in a simple manner the greater absorption of the umbra and penumbra. Under the intense radiation from the internal layers, the cooled masses which at any moment form the nucleus of the vortex will be able to maintain their low temperature, but as they are heated they will be replaced by new masses aspirated from below, which will flow radially towards the exterior above the photosphere. This process will continue until sufficient energy has been liberated to produce aspiration. During the outward movement the circulation around the centre of the spots will rapidly decrease and the radial component will prevail.

The radial outward movement at the level of the reversing layer causes a depression and a corresponding radial inflow into the upper layers. As a result of the sun's rotation the inflow will assume the form of a spiral, which may account for the appearance of hydrogen and calcium in spectroheliograms.

Since this spiral form is determined by the direction of solar rotation and not by the rotation of the underlying photospheric vortex, these spiral structures will not change their direction when the magnetic polarities change at the commencement of a new cycle of solar activity. If each spot formed an independent vortex, the bipolar ones would appear only by chance. To explain the frequency of these systems Hale supposed they were formed by a kind of ring whose two spots represent the intersection with the photosphere. Half the ring, according to this idea, belongs to the solar chromosphere, while the other half, dynamically the more important, forms a subphotospheric link between the

spots. Developing this conception, Bjerknes puts forward the hypothesis that all sunspots may belong to a single zonal vortex which surrounds the sun approximately along a parallel of latitude and produces a spot every time it passes from the photosphere to the reversing layer or vice versa. The hypothesis may be propounded in two different ways: the zonal vortex may almost entirely belong to the solar atmosphere and occasionally sink below the photosphere, from spot to spot of a binary system. Vice versa, it may be almost entirely

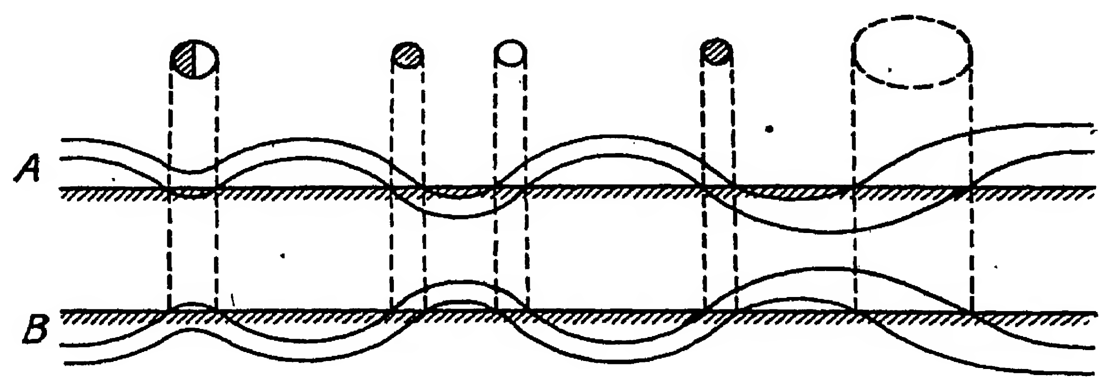

FIG. 133. Formation of sunspots according to Bjerknes' hypothesis.

subphotospherical and occasionally ascend into the atmosphere from spot to spot of a bipolar system.

The zonal vortex has the advantage of combining in itself the outstanding features observed in sunspots, viz.:

(*a*) that the spots of one and the same cycle appear in a limited zone of latitude and are generally of the bipolar type;
(*b*) that the axis of each binary system tends to become parallel at the equator;
(*c*) that the binary systems of the same cycle show on the whole the same polarity succession;
(*d*) that at their first appearance the groups are frequently bipolar;
(*e*) that a single spot usually represents the last phase, one of the components having become diffused and invisible before the other;
(*f*) that a companion of a single spot appears as follower if the spot of origin possesses the polarity belonging to that particular cycle and appears in the preceding position in the reverse case.

This theory offers an advantage in that the progression of sunspot phenomena from the highest to the lowest latitudes is reduced to a periodic movement of the whole zonal vortex, while the reversal of polarity from cycle to cycle might be accounted for by reversal of the rotation of the zonal vortex. A similar phenomenon might occur if there existed on the sun a general circulation from the poles to the equator at the level of the photosphere, which may probably be admitted if strata of different densities exist beforehand in the sun's interior. The simplest example of stratified circulation is depicted in Fig. 134; here it is assumed that the highest level has a circulation near the surface, from the poles to the equator, and conversely from the equator to the poles in the underlying strata. The next lowest stratum would thus circulate from the equator towards the poles in its upper part, and the one below it from the poles to the equator, and so on.

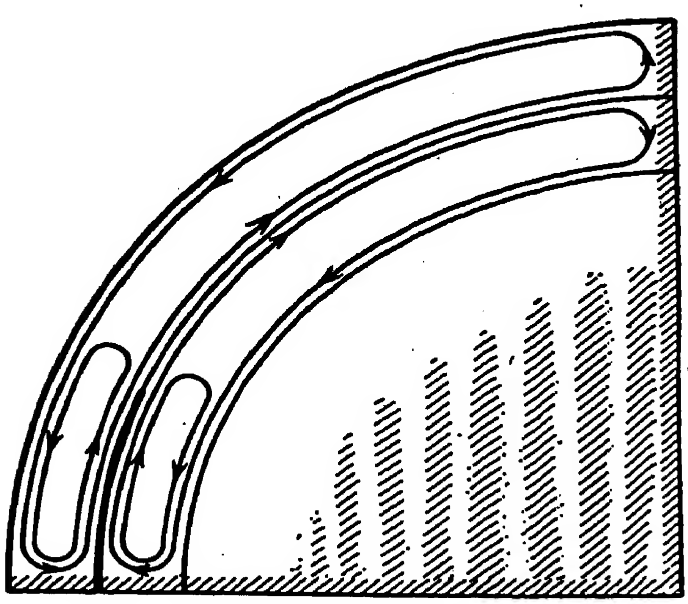

FIG. 134. General circulation on the sun (Bjerknes).

Bjerknes observes that such a circulation is thermodynamically possible, because the motive power is furnished by cooling of the photosphere due to radiation, by heating due to radiation from the interior in the lowest layers, and by contact with the first internal layer. Thus the photosphere may be considered to function like a thermal machine.

On the earth the currents circulate from the equator to the poles at the highest levels, and from the poles to the equator at the lowest levels, the principal source of heat being the ground level at the equator. On the sun it is difficult to foresee what the direction of circulation will be, but once circulation has started it will continue in that particular direction. Assuming that this circulation in the upper layers of the photosphere is directed from the poles to the equator and in the next lower layer from the equator towards the poles, we

can at once conclude what will happen on account of the sun's rotation.

As a matter of fact the great internal masses of the sun on both sides of the equatorial plane and around the axis of rotation (shaded areas in Fig. 134), which participate less in the general circulation, will move almost as a rigid body. On the other hand, the masses participating in the circulation will follow the same general law as exists on the earth, and hence the masses moving from the pole to the equator will lag behind, while those moving from the equator to the poles will proceed ahead towards the rigid or apparently rigid nucleus. Hence, of those taking part in the general radiation, the highest level would, according to this hypothesis, move at an increasingly retarded rate from the equator to the poles, and this would account for the equatorial acceleration, which might more aptly be termed a "retardation at high latitudes."

During their slow movement from the poles to the equator, the masses forming the surface of the photosphere must gradually cool down. Consequently the sun should have its highest temperatures at the poles and its lowest at the equator. The theory says that such differences of temperature are relatively too small to permit of their being measured by our experimental means. But we cannot rule out the possibility of there being greater differences of temperature if, for instance, with greater internal stability of the sun there is a decrease in depth of the solar vortices and of the individual layers taking part in the stratified circulation. As already stated, Emden's theory also leads to the conclusion that the sun's temperature is greatest at its poles.

Summarizing, it would seem that sunspots depend on intense local circulations and the equatorial acceleration on slow general circulation. It remains to be seen whether the two hypotheses can be made to tally in such a manner as to explain the appearance of spots at intermediate latitudes and their characteristic periodicity. In regard to this it should be noted that the greatest temperature contrast exists on either side of the equator, where the cooled masses of the photosphere which have continued to radiate from the moment they started from the poles descend and come into contact with

the hot ascending masses of the circulating layer immediately below.

This circumstance produces favourable conditions: on the one hand because the general circulation is concentrated at low latitudes as indicated by the curves in Fig. 134, and on the other hand because of the formation of other vortex zonal rings which produce spots. If these rings have a certain duration, they may be set in rotation by the general circulation in low latitudes, and the reversal of polarity at each cycle may be accounted for by assuming the existence of two zonal vortices, of opposite rotational directions, which are carried along by the general circulation (Fig. 135).

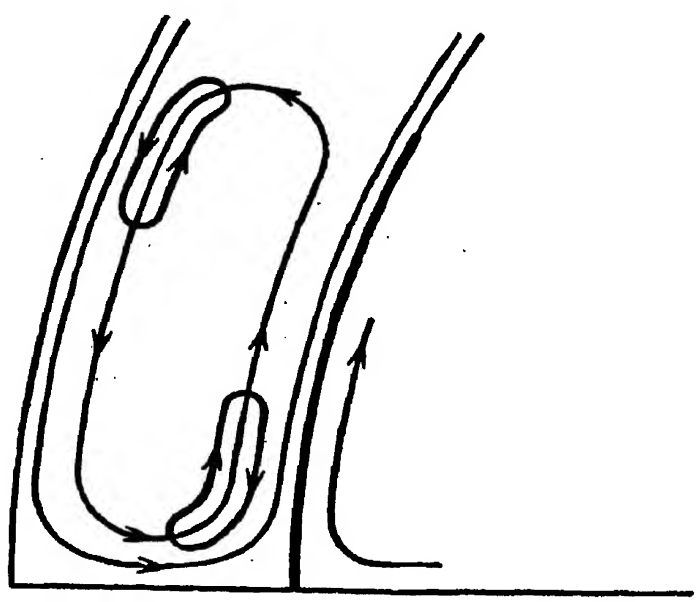

FIG. 135. Formation of zonal vortices having opposite directions of rotation (Bjerknes).

If the circulation between the poles and the equator occupies a period of several years, as seems possible from the hypothesis propounded, a period of 22 years for the complete revolution of the zonal vortices does not seem unreasonable.

The formation of the mechanism, which, as Bjerknes observes, is dynamically and thermodynamically possible and can better be treated in a more complete theory, is in good accordance with the facts observed: the spots of the new cycle with opposite rotation and opposite polarity will appear at high latitudes, while those of the old cycle will disappear in the whereabouts of the equator.

When the zonal vortex plunges and disappears at the equator the only spots will be those of the new cycle, which then attains its full development. This vortex having in turn approached the equator, the first one will reappear at high latitudes and will produce the spots of the next cycle with their reversed polarities, and so on.

In prominences, too, as already stated (page 154), circulating currents are in evidence which follow the spots in the

zones they occupy; at high latitudes, on the other hand, currents are observed which proceed from the intermediate latitudes towards the poles and which commence at about the same time as the spots reach the lowest latitudes. For faculae it will be remembered (page 82) that a general movement from the equator to the poles has been observed. These systematic currents gain considerable importance in confirming and developing the theory and the hypothesis which we have briefly outlined here.

Theories on the Constitution and Formation of the Corona

If little can be said to explain the constitution of the sun, it is still more difficult to propound any hypothesis regarding that of the corona and how it exists around the sun. If the corona were anything like our atmosphere the resulting pressure at the sun's surface would be tremendous, whereas we find very small pressures as far down as the reversing layer. Regarding the tenuity of the material constituting the corona, to which we have already referred (page 257), Newcomb, recalling how the great comet of 1843 passed the sun at a distance of three or four minutes of arc from its surface and thus just traversed the corona, observes that at that epoch its velocity was 550 km/sec, and at that speed the comet passed through 500,000 km of the corona without suffering any visible disturbance or retardation.

In order to form an idea what would have happened if the comet had encountered even a highly tenuous atmosphere, it need only be remembered that meteors are instantaneously and completely vaporized by the heat developed on encountering the earth's atmosphere at altitudes between 100 and 150 km, viz. at a height at which the atmosphere is so thin that it entirely ceases to reflect the sun's light. The velocity of meteors varies from 30 to 60 km/sec. Bearing in mind that the resistance and the heat developed increase at least in proportion to the square of the velocity, we can easily imagine what would be the fate of a body or group of bodies, such as a comet, when passing through many hundred thousands of kilometres even of highly rarefied atmosphere at a velocity of more than 500 km/sec. The great comet of 1882 also

passed very near the sun's surface and was so much brighter than the corona that it could be seen in broad daylight.

So we must conclude that the corona cannot be considered as a real and tangible atmosphere surrounding the sun. On the other hand, we know from the study of its spectrum that it is composed of highly ionized gases which produce the emission lines, but the inner corona also shows a continuous spectrum, while Fraunhofer lines are observed in the outer corona.

Numerous theories have been propounded in previous times, as for instance Huggins's electrical theory, Ebert's magnetic theory or Schaeberle's mechanical theory, to mention only a few. It is certain that nowadays, with modern knowledge of atomic physics and radiation pressure, the existence of the corona can be explained in a more satisfactory manner. Since the corona must be composed of free electrons and ionized gases, it will be understood why Schwarzschild suggested that the corona consists of an "electron gas," viz. a gas with very long, free paths capable of reflecting and polarizing light. When later, as in Störmer's theory, it is supposed that the electrically charged particles move under the influence of the sun's magnetic field, we can also explain the different shapes assumed by the coronal streamers at the poles and at the equator during the cycle of solar activity.

According to Mitchell, who also comes to the conclusion that the corona largely consists of electrons, it might be considered similar to nebulae which become luminous through the effect of radiation from the stars immersed in them.

Anderson calculates, on the basis of convective equilibrium, the actual molecular weight of the material constituting the corona, and finds good agreement with the atomic weight of the electron. The thermal radiation of the internal corona is naturally a maximum near the sun's surface, and so is the intensity of the photospheric light reflected by the electrons. It thus seems probable that the coronal radiation originates in the electron, whilst the radiant energy would seem to be due to two causes:

(*a*) to thermal radiation resulting from impacts;
(*b*) to reflection and diffraction of the photospheric light.

We can thus account for the complex appearance of the coronal spectrum, both in the inner and in the outer corona. The collisions would seem to take place between the electrons on the one hand and the once or several times ionized atoms on the other hand. The latter will be more numerous at the sun's surface, and few of them will be found in the outermost corona which give rise to the lines of the supposed element coronium.

As regards the changes of shape of the corona during the eleven-year cycle, we have already stated (page 249) that the coronal streamers are very sensitive to disturbances of the photosphere and chromosphere and hence to the presence of spots, flocculi and prominences, whose immediate vicissitudes they follow. The coronal rays would merely be the trajectories described by the electrons under the action of the magnetic solar field, and their shape variations in relation to the eleven-year cycle would be due to the emission of very numerous electrons expelled from the active regions, principally from the prominences.

Moore found that the Fraunhofer lines in the coronal spectrum indicate an outward movement of the order of 26 km/sec. The great coronal changes observed from the maximum to the minimum of solar activity and the linear relationship that is found to exist between prominences, coronal streamers and arcs, show that fairly rapid changes must take place also in the position of streamers. As Rosseland observes, the chromosphere, prominences and corona must form an intricate complex of dynamic phenomena, based in theory on the expansive movement of material receding from the sun. As we have seen, this movement causes the St. John effect (page 190). The clouds of particles emitted from time to time by the sun influence the structure of the chromosphere and are very probably responsible for the development of the corona.

Recently, among the numerous existing theories of the corona, a new one was suggested by Kiepenheuer which would account for the various forms of the corona at maximum and minimum. It is natural to suppose that the speed of expulsion of the clouds of material emerging from the photosphere during minimum activity will be less than during maximum. The magnetic forces formed in the corona may, according to this

theory, be better able to act upon the clouds in the first case than in the second, and the trajectories calculated on the strength of this theory are a good reproduction of the maximum and minimum types of corona.

However, it must be acknowledged that the constitution, shape and variability of the corona are as yet unsolved problems.

Interior of the Sun and Origin of Solar Heat

Knowing that the stars are gaseous spheres with a certain surface temperature, and making use of atomic physics, Eddington developed a theory on the internal constitution of the stars and hence also of the sun. On the basis of this theory, Russell presents a picture of what actual conditions may be in the interior of the solar globe and what hypotheses as to the origin of its heat are most plausible.

The pressure, density and temperature of the hot, luminous sphere of gas at the exterior must be constantly increasing towards the interior, and since the density of the external layers is much less than that of water, while the mean density is greater, it follows that the density of this sphere towards the centre must be considerably greater than that of water. In view of the weight of the material above it, the central pressure is calculated to be of the order of a million tons per square centimetre, while the central temperature (provided that, as seems to be the case, the gas laws apply) would be of the order of ten million degrees absolute. It is not possible to reproduce this temperature in terrestrial laboratories in order to study what happens with the material under such conditions; but indirectly it is nowadays possible to produce in vacuum tubes falls of potential that cause electrons to undergo just as violent atomic bombardments as if they were subjected to impacts in a gas at a temperature of more than a billion degrees. The behaviour of the atoms under these conditions gives us an idea of what happens in the sun's interior.

We thus find that, in spite of the high pressure of the internal layers, the material must remain gaseous everywhere, and the atoms must be so highly ionized that they lose nearly all their orbital electrons. Considering what conditions of pressure and temperature must exist at the sun's centre, and knowing the

ionization potentials, it may be anticipated that atoms with an atomic number lower than six or seven (carbon or nitrogen) must have lost all external electrons, thus becoming reduced to bare nuclei. The calcium atoms (atomic number 20) only retain two of the innermost electrons, and the iron atoms (atomic number 26) only two or three.

Eddington's theory finally arrives at the important conclusion that the highly ionized matter continues to behave as a "perfect gas," because the space occupied by the atoms when deprived of their electrons and of the free electrons is always small in comparison with the total volume. On the other hand, though deprived of their electrons, the atoms nevertheless preserve their characteristics, since the collisions occurring in the sun's interior are not always so violent as to transform one element into another, and hence they cannot make the nuclei lose their identity. So it must be supposed that, if these nuclei could be extracted from the sun's centre, they would regather of their own accord the electrons which they possessed before being ionized.

Through the gas in the sun's interior there is an emanation of radiant energy in all directions, from the centre to the electrons and ions, and since, below the photosphere, the laws are applicable which govern radiation from a black body, we can apply these same laws for interpreting the conditions ruling in the sun's interior. One of these conditions, Wien's well-known law of shift, says that the wavelength corresponding to the maximum intensity of a perfect radiator, as is a black body, multiplied by the absolute temperature, is equal to a constant. Knowing the constant it can at once be calculated that, at a temperature of ten million degrees, the radiation must have a very short wavelength (of the order of 3 angstroms), thus being of the kind which physicists call "soft X-rays."

Another law, "Stefan's law," says that the total energy of a perfect radiator is equal to the fourth power of its absolute temperature multiplied by a constant. At ten million degrees the flux in every direction is 8×10^{12} times greater than that emitted by the photosphere. It is thus a flux of inconceivable intensity which moves through the atoms and is absorbed by them and re-emitted, proceeding gradually towards the exterior.

With so great an energy the radiation pressure is enormous, and this pressure is likewise exerted in every direction, partly sustaining the great weight of the material above it. According to Eddington's calculations the radiation pressure amounts to about 5 per cent of the total pressure, the density at the centre would be twenty-eight times that of water, the central pressure thirty-six million atmospheres and the temperature thirty million degrees.

The temperature of the photosphere depends on the velocity at which the heat can emerge from the sun's interior, and this velocity depends in turn on the opacity of the material at the base of the photosphere which prevents the intense internal radiation from escaping more rapidly.

We have often wondered what may be the origin of such enormous energy as that radiated by the sun unstintingly in all directions and in a constant or almost constant manner, in the short time during which we have measured it. Knowing the "solar constant" (page 304), we can calculate that the sun radiates about 90,000 calories per square centimetre per minute, viz. 84,000 horse-power, acting continuously for every square metre.

The old theory of meteorites falling upon the solar globe in order to replenish its heat, and the contraction theory suggested by Helmholtz, have had their day and are now acknowledged to be inadequate to account for the enormous energy radiated by the sun at the present day and for such a long time in the past, not to speak of what it will be in the future. The amount of energy required is certainly hundreds of times greater than that which could be furnished by the sun's potential gravitational energy. The temperature of the sun is still so high that a large part of its energy must be considered to be stored away in its interior, while the remaining portion at its present rate of flux would have shone for too short a period according to the geological evidences we find on the earth.

Nowadays we must remember that the immense quantity of energy liberated by the sun has its origin in the nuclei of the atoms. We know that sub-atomic forces are tremendous, and experience tells us that radioactive substances, on being transformed and thereby emitting electrons and α particles at a great velocity, liberate huge quantities of energy

sufficient to keep the sun alive for the required period. It is true that there are no traces of radioactive elements in the photosphere, but in view of what we have said about the constitution and composition of the sun, this fact is no proof that they may not exist at such depths as to escape our means of observation. It may also be anticipated that atoms of elements heavier than those known hitherto and recently discovered by Fermi and his collaborators, liberate large quantities of energy when undergoing transformation.

It may also be supposed, according to modern conceptions of relativity, that the solar globe in course of radiation must be continually losing a certain amount of its mass. This loss must take place in some of the component atoms, with the liberation of a corresponding quantity of energy. As far as we know nowadays, the transformation of hydrogen into other elements liberates energy when the electrons and protons approach each other to form the nucleus of a heavy atom, because the atomic weight of this atom is always less than the weight of the number of hydrogen atoms theoretically required for its formation.

Another supposition is that the charges of an electron and of a proton, when encountering each other under conditions and in ways unknown to us, are neutralized so as to destroy each other. In that case the corresponding energy would first manifest itself as a radiation of some kind and then as heat. In comparison with this process, which is still a mystery to us, the radioactive processes or the formation of elements heavier than hydrogen demand much less energy; in this way we could explain how solar radiation as we observe it nowadays has transformed and will transform into radiation such small amounts of the sun's mass that its past life of thousands of billions of years and a perhaps even more extensive future can be accounted for.

CHAPTER VI

RADIATION AND TEMPERATURE OF THE SUN

How the Intensity of Solar Radiation is Measured

The radiant energy we receive on the earth from the stars is on the whole exceedingly small, so that it has only been possible to measure it with the most powerful instruments and for the most brilliant heavenly bodies. But the radiation we receive from the sun is very intense, and as it is important for us to know its amount and whether it undergoes any fluctuations in course of time, various instruments and methods have for years past been devised in order to determine this radiation and to deduce from it the actual temperature of the photosphere.

These determinations are made on the earth's surface, and it is necessary to free them from the effect of the terrestrial atmosphere. We can then refer to the intensity of solar radiation that would be received by the earth at its mean distance from the sun, viz. to the quantity of energy that falls during unit time on unit area of a surface situated outside the terrestrial atmosphere and placed at right angles to the direction of the sun's rays.

The instruments used are called *pyrheliometers*, *bolometers*, *spectrobolometers* or *radiometers*, according to the principle on which they are based or according to whether they serve for the measurement of radiation in integrated light or for selective determination in different wavelengths.

As early as 1837 Pouillet constructed his well-known pyrheliometer, consisting of a copper vessel with a flat and blackened bottom, filled with water and containing a thermometer bulb.

The amount of solar radiation is determined by observing the change of temperature in a given interval of time, first with the instrument in the shade, and then directing the instrument towards the sun, noting the rise of temperature due to solar heating during the same interval. The observation is afterwards repeated in the shade, and in this way we can correct the

mean increase of temperature during one minute as obtained with the instrument in the sun by the mean loss indicated by the readings in the shade. This gives us, for a mass of water and copper of known heat capacity, the increase of temperature during one minute due to the sun's rays, which fall perpendicularly upon the instrument and are absorbed by the known area of the bottom of the box. We must also allow an extra correction of 2·5 per cent because of the loss due to reflection from the blackened bottom.

The radiation determined in this manner is weakened by its passage through the terrestrial atmosphere, which for the

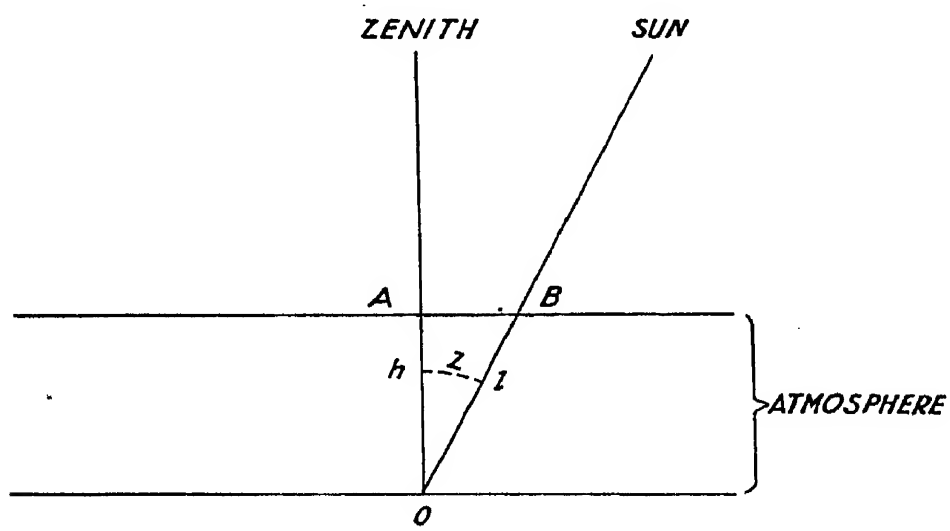

FIG. 136.

practical purpose of this absorption may be considered to be about 150 or 200 km. high and of small thickness compared with the earth's radius. If the sun is not exactly at the horizon but 15° or more above it, and the length of path of its rays in the atmosphere is represented by l, the thickness of the atmosphere by h and the zenith distance at the moment of observation by z, we may write with sufficient approximation:

$$l = h \sec z.$$

Bouguer and Lambert proved independently in 1760 that when a ray traverses a transparent homogeneous medium of a thickness s, the original intensity I_0 is reduced according to a rule which is given by the equation:

$$I = I_0 \, a^s,$$

where I is the intensity actually received through the medium of thickness s, and a a constant representing the proportion of radiation transmitted by unit thickness. Pouillet applied this formula to his observations, taking as unit thickness the thickness of the atmosphere with the sun at the zenith, and thus arrived at the equation:

$$I = I_0\, a^{\sec z}$$

Taking the logarithms, we get:

$$\log I = \log I_0 + \sec z \log a$$

We can draw a graph (Fig. 137), taking as abscissa the secants of the zenith distance and as ordinates the corresponding values of $\log I$, which gives us a straight line whose ordinate at the origin is the logarithm of the solar constant I_0.

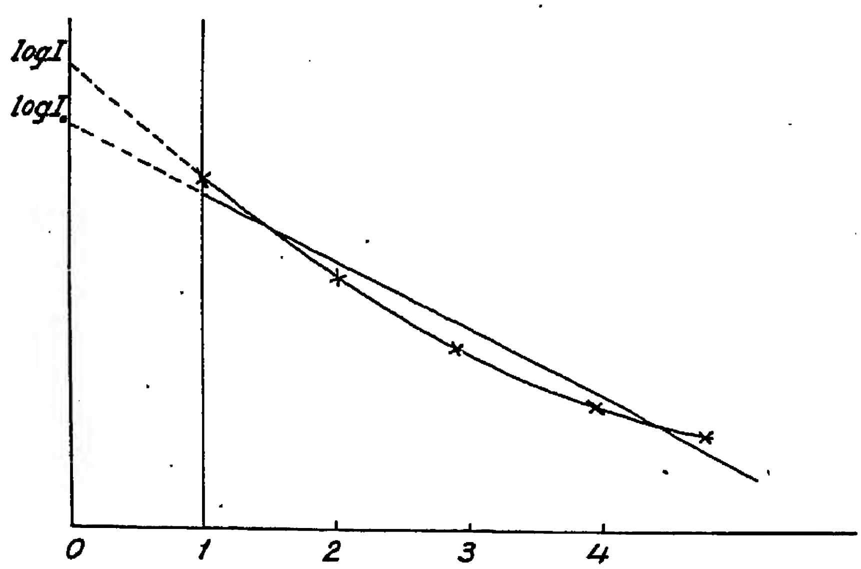

FIG. 137.

Pouillet, drawing the straight line which gave the best fit to the experimental points, found for I_0 the value 1·76 calories per square centimetre and per minute. We shall see (p. 304) that this number is less than that determined later by more precise methods. As a matter of fact the points observed are actually on a curve, which makes the value of I_0 higher, as the Bouguer–Lambert formula only holds good for monochromatic radiation and it may not be assumed that a is invariable.

Numerous instruments of increasingly high perfection have been constructed since Pouillet's time. We will examine some of the most important. They may be divided into *relative* instruments and *absolute* instruments; the former serve for relative measurements, from which we can change over to absolute measurements by referring to a standard instrument.

Standard instruments serve for absolute measurements and furnish results directly in calories.

To the first type belong Pouillet's pyrheliometer to which we have already referred, and the silver disc pyrheliometer, which is simply that of Pouillet modified by Tyndall, an iron box containing mercury being in this case substituted for the

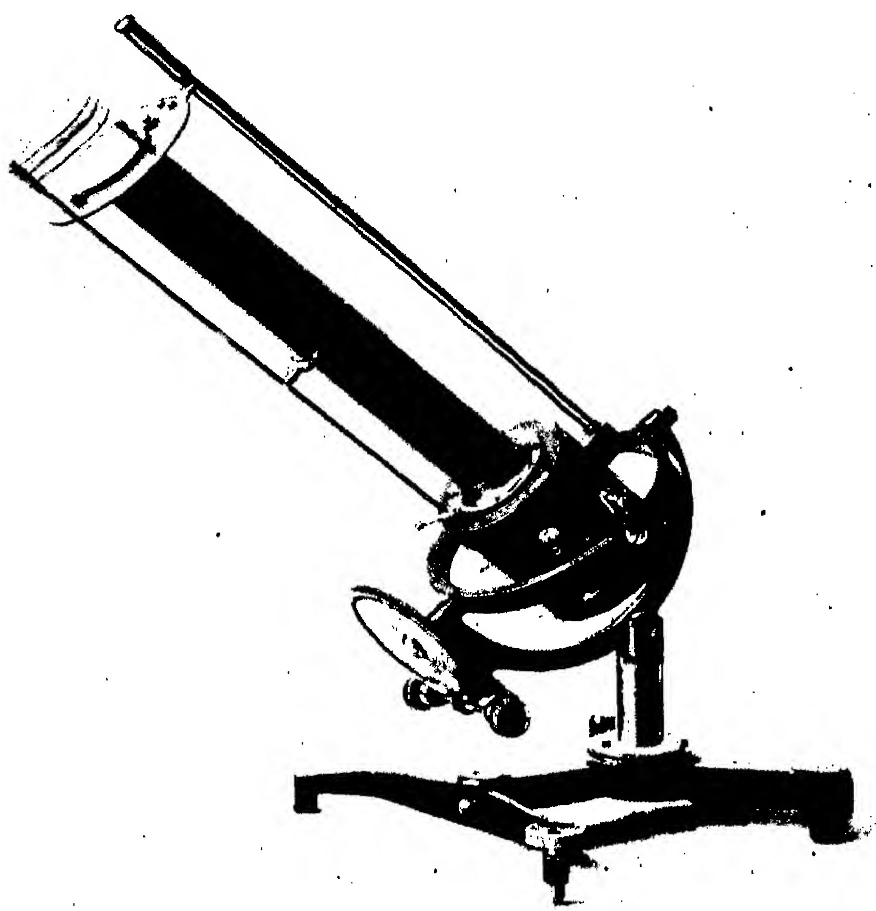

FIG. 138. Silver disc pyrheliometer (Smithsonian Institution).

copper box containing water. This instrument has been exhaustively used, especially by Abbot and his collaborators of the Astrophysical Observatory of the Smithsonian Institution at Washington, for his classical series of measurements which have been carried out in many parts of the world.

To the second type belongs the *compensation pyrheliometer*, constructed in 1896 by K. Ångström, which has also found very extensive application. It consists of two thin manganin strips of known area, blackened in the part facing the sun; in the rear part of each blade is a thermocouple for deter-

mining its temperatures. An electric current of a certain strength is passed through one of the strips while the other is exposed to the sun. When the galvanometer connected to the thermocouples indicates equality of temperature, it is assumed that the known quantity of heat introduced by the electric current is equal to that absorbed by the strip exposed to the solar rays.

For better balancing of the measurements, the strips are afterwards reversed so as to expose to the sun the strip through which the electric current was first passed, and the mean result is then taken. After correction for reflection losses the results are deduced directly in calories per square centimetre per minute. The instrument is so adjusted that it can easily be kept directed towards the sun by following its diurnal motion.

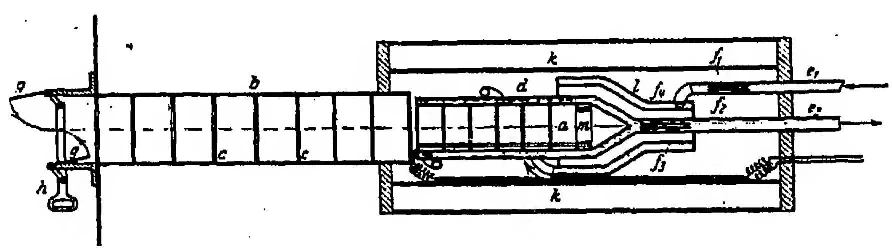

FIG. 139. Plan of Abbot's water-flow pyrheliometer.

In pyrheliometers of this kind there is a source of error which is difficult to allow for, as it varies according to different conditions of observation, viz. the fact that a portion of the heat produced by absorption of the sun's rays in the blackened receiver is dispersed in the air or re-radiated in larger wave-lengths; this portion of the heat has of course no effect on the thermometer or the thermocouple and is therefore lost. To eliminate this source of error several other types of pyrheliometers have been designed, notably by Abbot, for absolute measurements.

One of these is the *water-flow pyrheliometer*, which is intended to make the heat-receiver reproduce in the best possible manner the conditions of a black body. The radiation absorbed by this instrument is not measured direct, but produces an increase of temperature which can be measured in a current of water surrounding the actual heat-receiver. The general characteristics of this type of pyrheliometer are seen in Fig. 139. Opening the cover *gh*, the radiation passes into

the interior of the blackened tube *b* through a number of diaphragms *c*. The calorimetric flask *k* connects the receiver *a*, which consists of a cylindrical blackened tube with a conical ending. Between the walls of *a* and the counter-walls *d* there is a flow of water, which enters by tube e_1 and leaves by e_2.

A differential electric thermometer composed of four thin platinum threads f_1, f_2, f_3, f_4 is connected to a Wheatstone

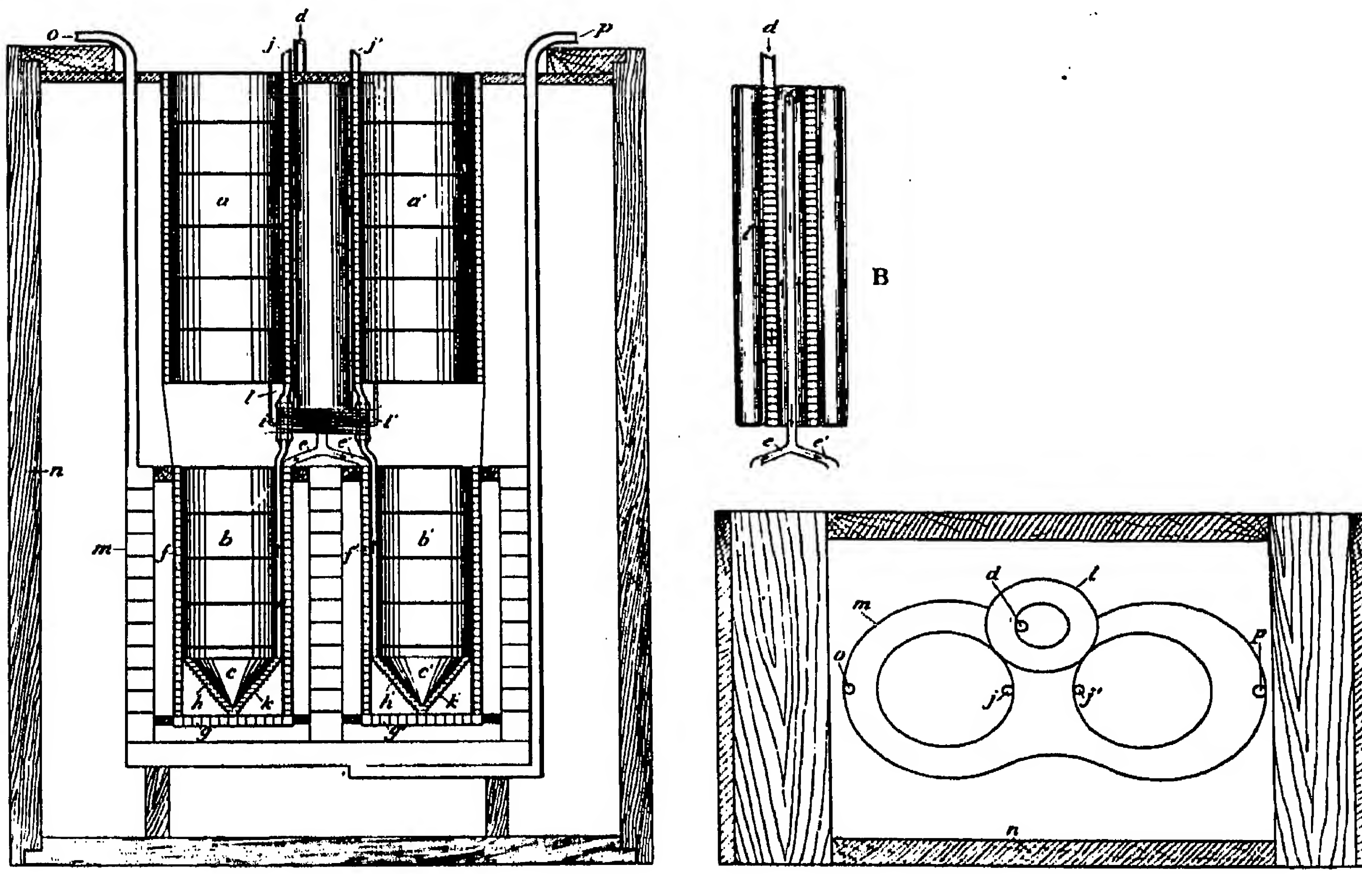

FIG. 140. Diagram of the standard water-flow pyrheliometer with double compensation chamber, designed by Abbot.

bridge, which in turn is connected to a very sensitive galvanometer. The pyrheliometer is protected against external variations of temperature by a Dewar vacuum flask. To allow for other slight sources of error, this pyrheliometer was subsequently modified and perfected (Fig. 140) so as to give finally, after numerous checks, an absolute scale (the Smithsonian revised scale) to which we can refer all values of the solar constant measured with several absolute or relative instruments.

After Macedonio Melloni had proved in 1842 that the calorific radiation is of the same nature as the visible radiation,

and that for research on radiations of great wavelength we can advantageously use rock-salt prisms, Langley designed about 1880 a very sensitive electric thermometer called a *bolometer* or *spectro-bolometer* (if used in conjunction with a spectroscope), which gave important results in the study of the distribution of energy in the solar spectrum.

The principle of this instrument, with which Langley succeeded in observing the solar spectrum up to 28,000 A, is shown in Fig. 141. The sensitive part of the bolometer consists

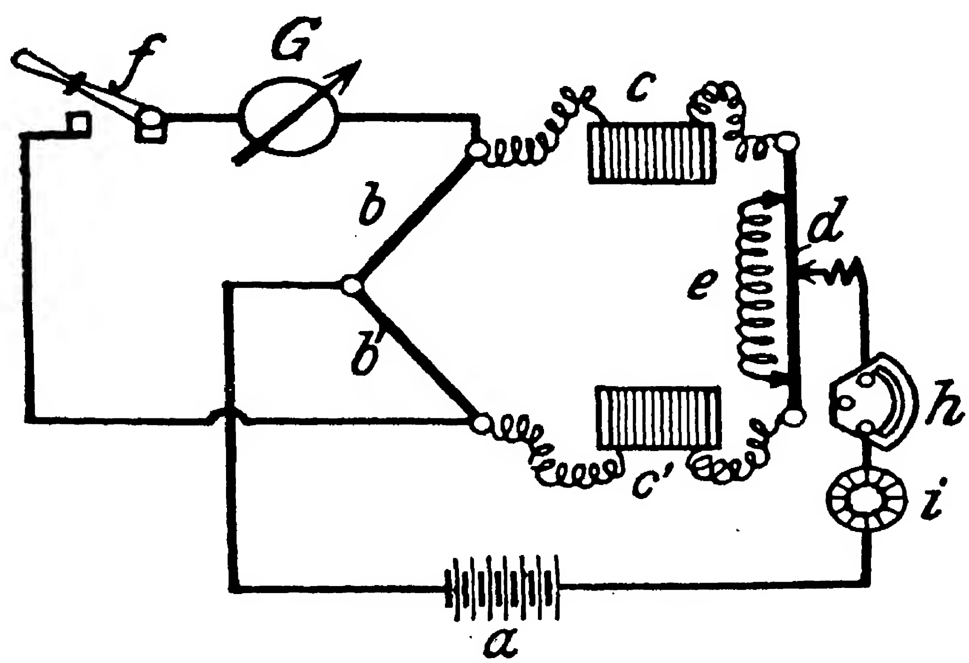

FIG. 141. Diagram of the Langley bolometer.

of two blackened platinum strips *b*, *b'*. These strips form the two branches of a Wheatstone bridge, balanced in such a manner that a galvanometer placed in circuit remains at rest. When solar radiation is allowed to fall on one of the strips, its resistance increases and there results a deflection of the galvanometer needle proportional to the heat produced by the radiation.

In Fig. 141 *c*, *c'* are two coils of manganin wire which constitute the resistances of the other two branches of the bridge. The resistances *e*, *d* serve for accurately balancing the bridge, *a* is a storage battery, *G* the galvanometer. The current, of the order of 0·1 amp, is indicated by the milliameter *h* and regulated by the resistance *i*.

A considerable improvement has been effected by con-

necting the receiver of this bolometer in vacuo: with a sensitive galvanometer it is possible to measure temperature variations of the order of 1×10^{-8} degrees.

For studying the radiation of different parts of the spectrum the bolometer is used in conjunction with a spectroscope, as shown in Fig. 142. The radiation passes through the slit *S*

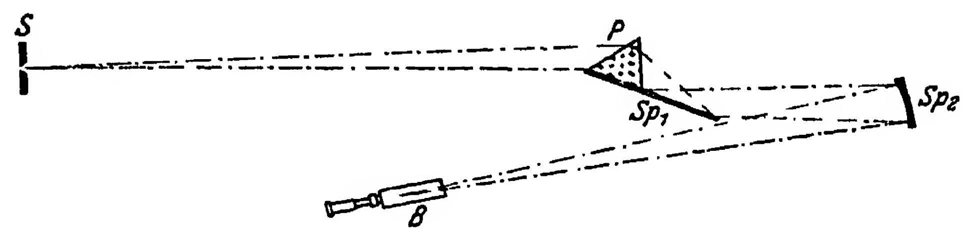

FIG. 142. Diagram of Langley's spectrobolometer.

and falls upon a rock-salt prism connected to a mirror Sp_1. A concave mirror Sp_2 reflects the radiation of the different parts of the spectrum back to the bolometer *B*.

The galvanometer readings may, instead of being taken

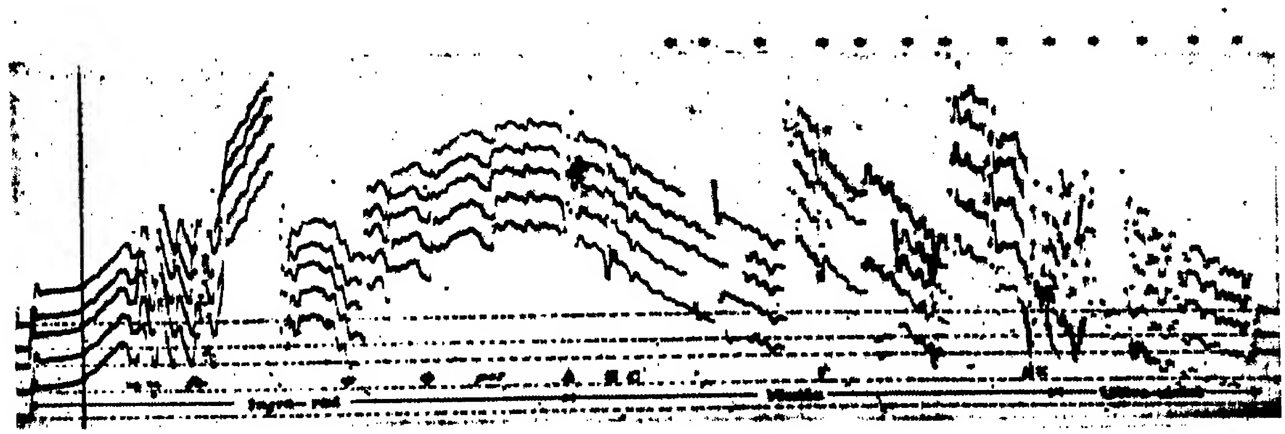

FIG. 143. Bolograms obtained by the Smithsonian Institution at Montezuma (Chile).

visually, be recorded automatically on a photographic plate which is kept moving vertically by a clockwork mechanism, whilst at the same time the spectrum is moved in front of the bolometer strip. In this case the instrument is called a *bolograph*. In the diagram (Fig. 143) a series of five bolograms is reproduced, which are obtained by Abbot from the infra-red to the ultra-violet. We can see clearly bands and absorption lines, indicated respectively by Greek and Latin letters. In the interrupted points of the curves of the five bolograms the

intensity scale has been altered to make the curve fit into the space available.

Among the numerous determinations of the total energy radiated by the sun are those carried out by Amerio (1909–1911) with an integral receiver made from a hollow sphere with stout inner and outer walls of silvered brass representing the nearest possible approach to the conditions of a black body together with a spectro-bolometer. Amerio carried out his observations at four stations at different heights above sea-level in order to determine the absorption exercised by the terrestrial atmosphere for groups of different wavelengths. The highest of the stations was situated at the Osservatorio Regina Margherita at Point Gnifetti, which, at a height of 4559 metres, is, after Point Dufour, the highest peak of Monte Rosa.

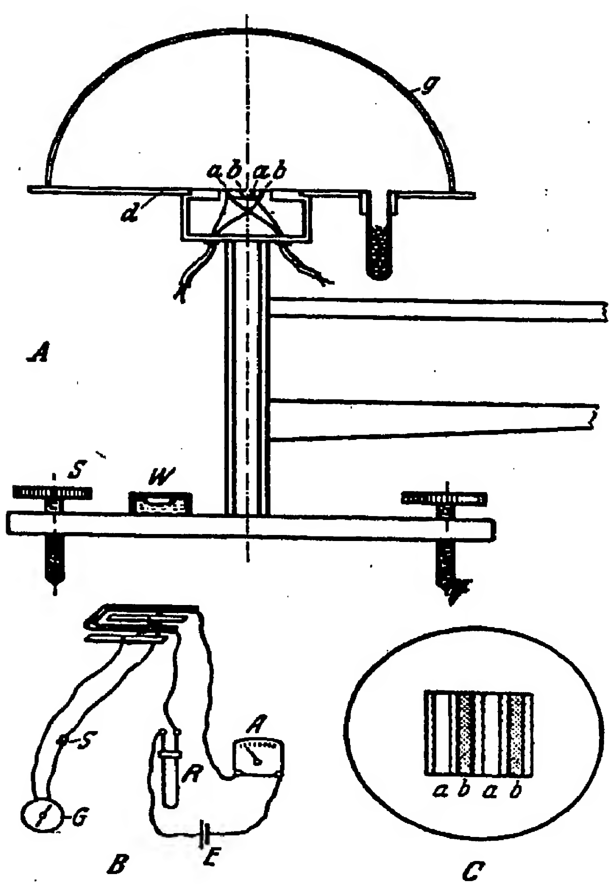

FIG. 144. Diagram of A. Ångström's pyranometer.

Observations at a high altitude of the solar constant were also effected by the De Filippi expedition (1913–14) in the Caracorum Mountains at the Depsang Highland of Central Asia, at 5367 metres above sea-level.

In view of the serious difficulties encountered in determining the transmission coefficients of the atmosphere in order to gather information from them regarding solar radiation, it has been found advisable to use in conjunction with the pyrheliometer and spectro-bolometer another instrument called a *pyranometer*, which is commonly employed in meteorology for measuring the radiation from the day and night sky.

By combining the measurements given by this instrument with those obtained at the same time with the pyrheliometer and spectro-bolometer, we can make an observation also at

one single zenith distance of the sun in order to obtain the solar constant, thus also utilizing days on which the sky is not perfectly clear.

The pyranometer consists of a flint glass hemisphere closed by a metal plate *d* and having at its centre four blackened

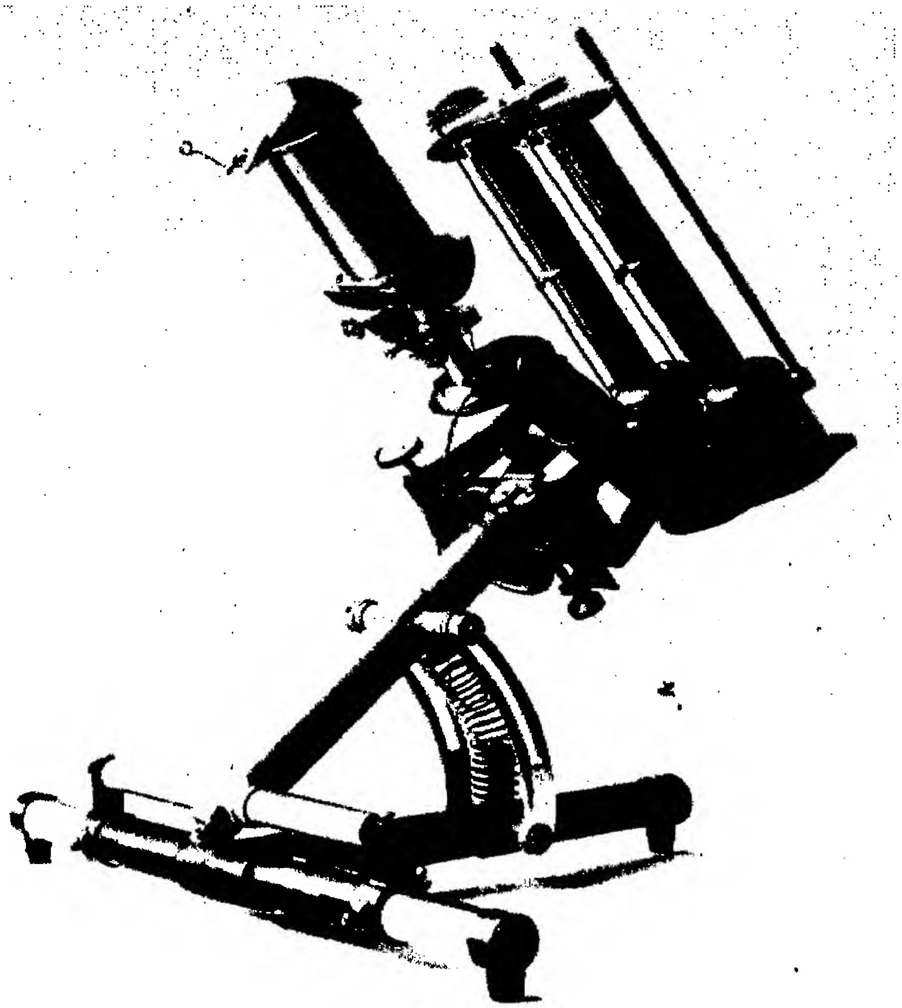

FIG. 145. Pyrheliometer and pyranometer used by the Smithsonian Institution of Washington.

strips *a b a b*. Bands *a* are afterwards whitened with magnesium and zinc oxides.

Behind the bands are thermocouples, which are connected to galvanometer *G*. On exposing the instrument to the sun a difference of temperature is obtained, since the blackened bands *b* absorb more than the white ones *a*, and hence a deflection of the galvanometer is produced. When the instrument is removed from the sun it is necessary to pass a compensating current through the white strips by adjusting the resistance *R*, in order to make the galvanometer needle return

to the zero of the scale. The radiation may safely be considered to be proportional to the square of the current-strength indicated by the milliammeter *A*. After several improvements the pyranometer has found frequent use at the stations established by Abbot in California, Chile and Africa for measuring the solar constant and its variations.

Although by the use of this instrument better results have certainly been obtained in determining the absolute solar constant, we cannot yet hope to arrive at an exact valuation of the absorption due to water vapour, however accurately we may measure the intensity of these absorption bands in the infra-red. The same is true for the transmission coefficients of the atmosphere with different wavelengths, and hence the results cannot yet be considered as strictly holding good for solar radiation outside the terrestrial atmosphere.

The Solar Constant and its Variations

As already stated (page 294), the solar constant is the quantity of solar energy received outside the terrestrial atmosphere by a surface area of one square centimetre positioned perpendicularly to the sun's rays, at the mean distance of the earth from the sun, during an interval of one minute. It is expressed in gram-calories and may, in the system of absolute measurement, be formulated thus:

$$\begin{aligned} 1 \text{ gm cal cm}^{-2} \text{ min}^{-1} &= 0{\cdot}01667 \text{ gm cal cm}^{-2} \text{ sec}^{-1} \\ &= 6{\cdot}977.10^5 \text{ erg cm}^{-2} \text{ sec}^{-1} \end{aligned}$$

Of course the higher we ascend into the atmosphere the nearer we approach the value of the solar constant. The table on page 306 gives an idea of the variations of this constant as a function of altitude, and it will be seen that its value outside the atmosphere must be somewhere about two calories.

If the different layers of the atmosphere were of equal transparency, we could extrapolate and calculate the solar constant from such data. Experience shows that in order to obtain a plausible result the observations have to be effected in the same place with the sun at different heights above the horizon.

The variation of solar radiation with the variation of the

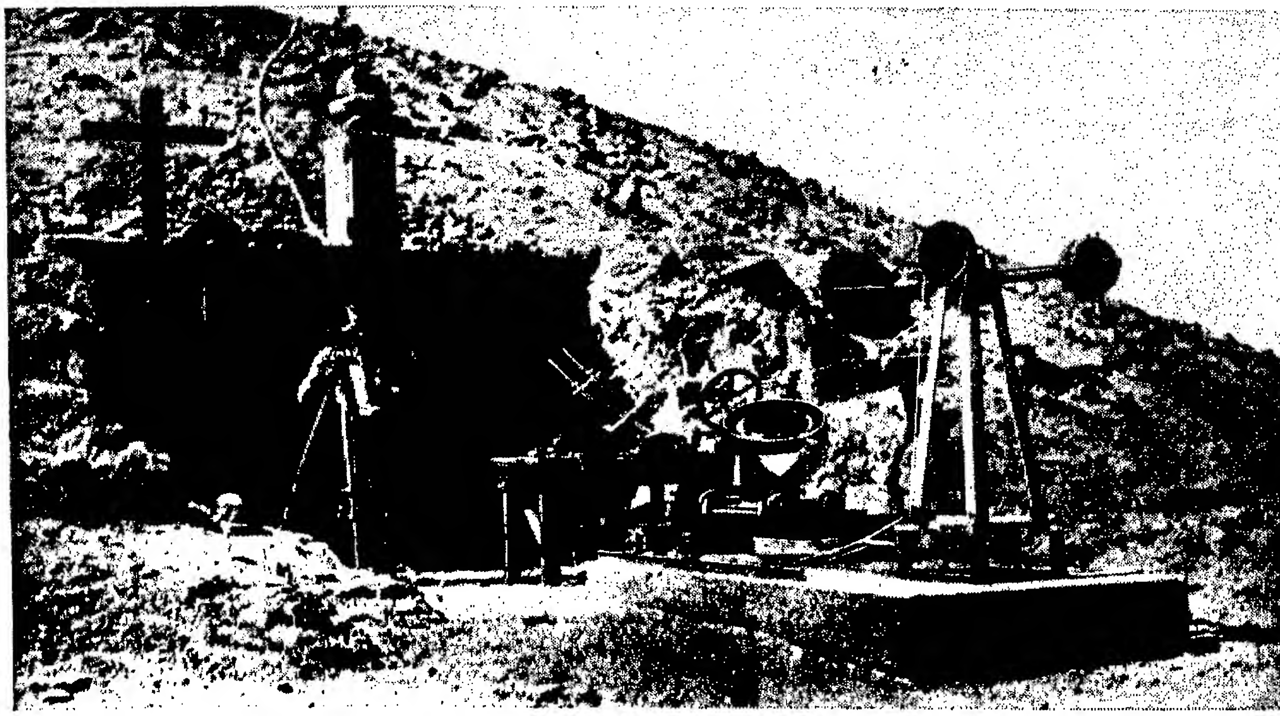

FIG. 146. Station of the Smithsonian Institution at Montezuma (Chile).

FIG. 147. Station of the Smithsonian Institution at Brukkaros (South-West Africa).

sun's height is seen, for instance, in Fig. 148, which shows the measurements effected by Götz at Arosa in the month of June. This variation is determined not only for the total

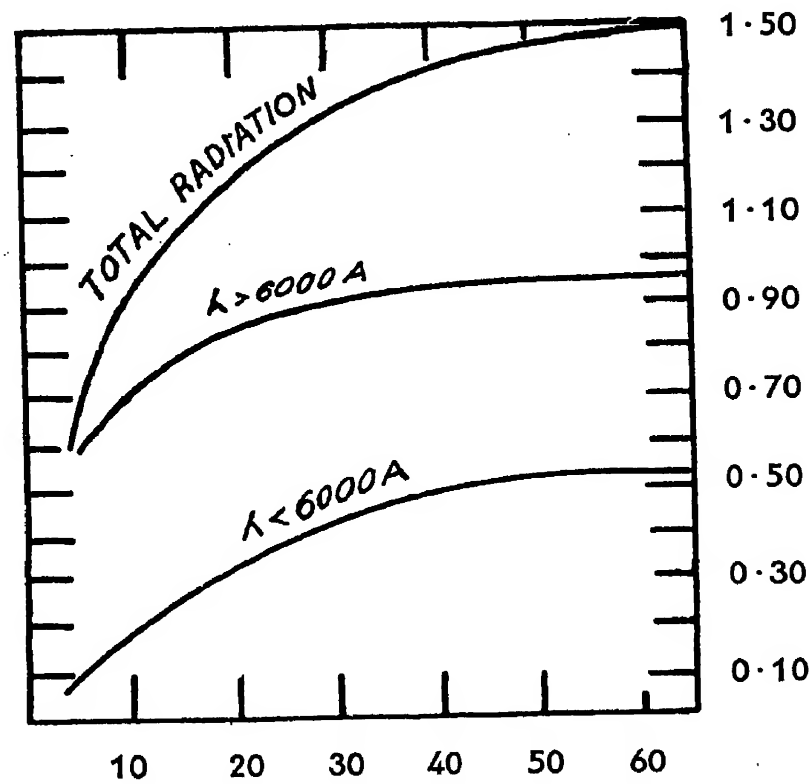

FIG. 148. Dependence of solar radiation on the height of the sun (Götz). (Abscissae: height of the sun in degrees; ordinates: gm cal $cm^{-2}min^{-1}$.)

radiation, but also for radiations in spectral regions of wave-length > 6000 A and of wavelength < 6000 A. The trend of the curves furnishes evidence that, when the sun is low on

Place of observation	*Height above sea-level*	*Energy in cal cm^{-2} min^{-1}*
	metres	
At sea-level	0	about 1·40
Davos	1600	,, 1·59
Jungfraujoch . .	3460	,, 1·63
Mount Whitney . .	4420	,, 1·72
Unmanned balloon	20,000	,, 1·89

the horizon, the radiations of smaller wavelengths are more or less completely absorbed by the atmosphere and that, at any rate when the sun is high above the horizon, the bulk of the total radiation always consists of red and infra-red radiations.

The problem of reducing all the observations made at different heights of the sun up to its maximum height, has been treated by several authors, who have calculated tables (as did Bemporad, for instance) reporting the radiation observed in unit mass of air as if the sun were always at the zenith of a given place.

In order to ascertain the solar constant we must also determine the transmission coefficient a, viz. as already stated (page 296), the loss which the total radiation sustains when traversing unit mass of air. To this end many researches have been conducted, which were complicated by the fact that there is a wavelength dependence in the sense that decreasing wavelengths have smaller corresponding values of a.

Müller was among the first to determine the selective absorption in the visual region of the spectrum, and found:

for 4500 A: $a = 0 \cdot 72$
for 5500 A: $a = 0 \cdot 81$
for 6500 A: $a = 0 \cdot 87$

A representation of the mean trend of the transmission coefficient according to the various wavelengths (which coefficient has been determined by several authors from the limits of transparency of the atmosphere for ultra-violet, 2850 A, up to 21,000 A) is given in Fig. 149. The absorption due to ozone bands causes the anomaly in the curve between 5300 A and 5900 A. Below 3300 A there is thus a considerable decrease of transparency due to ozone bands which seem to exist at about 40 km above the earth's surface.

For wavelengths below 4000 A it may be observed that:

(*a*) the decrease of transparency of the atmosphere with decreasing wavelength is considerably more rapid than in the region of the visible spectrum;

(*b*) the transparency of the atmosphere varies from day to day in the short-wave region to a much greater extent than in the long-wave region;

(*c*) the transparency of the atmosphere in the region of ultra-violet radiation increases more rapidly with the increase of height above sea-level than for radiation in the visible spectrum.

In the extrapolations required for determining the solar constant we must therefore allow for many sources of disturbance and establish the transmission coefficients for many spectral regions. On the other hand, the value of the solar constant cannot be the real one unless the measurements taken embrace the sun's total radiation. But this is not possible, for below 2850 A solar radiations cannot reach us on account of absorption by terrestrial ozone, and above 25,000 A the sun's rays are again almost completely absorbed by the water vapour and carbon dioxide bands.

We have seen what value was first obtained by Pouillet for

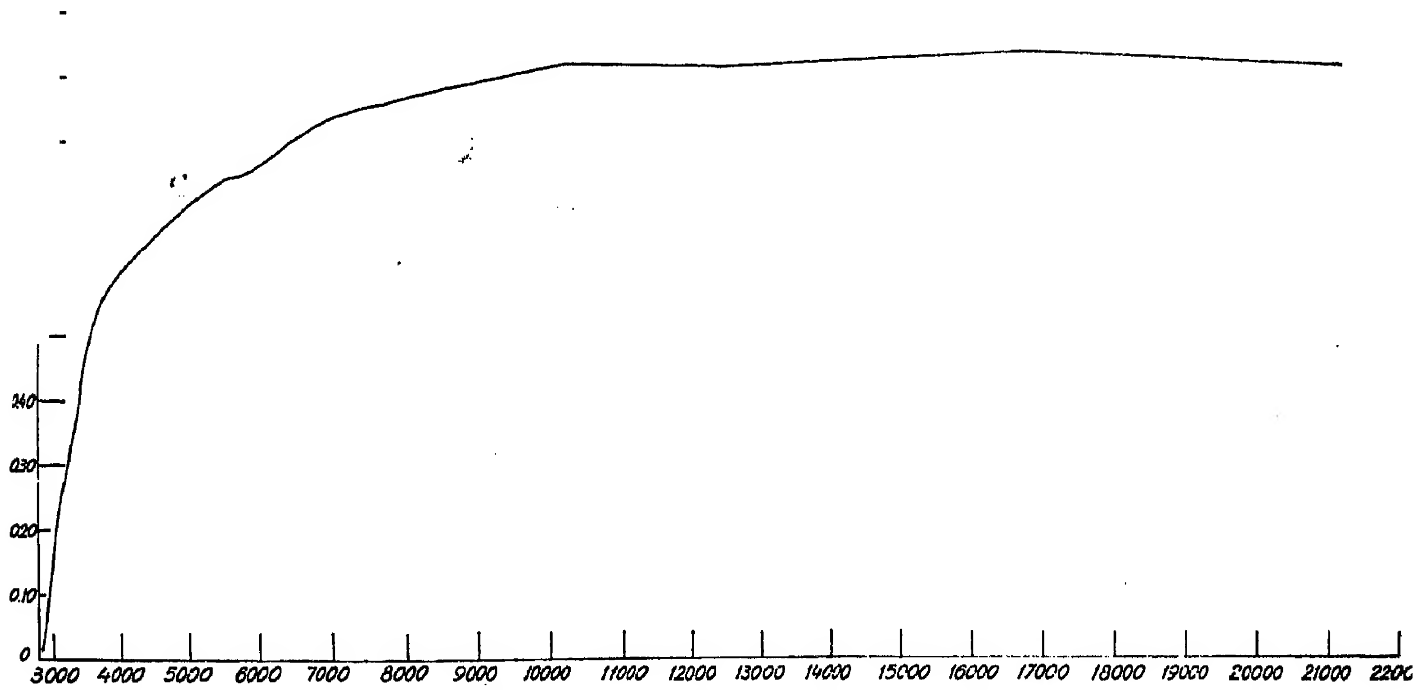

FIG. 149. Variation of the transmission coefficient with wavelength.

the solar constant. With the invention of the spectrobolometer Langley fixed the value at 1·92 calories, confirmed later by Wilsing's measurements at Potsdam. Extensive measurements by Abbot and his collaborators at Washington and other measurements carried out at stations purposely selected in view of altitude and transparency of the air in different parts of the globe (California, Chile, South Africa), have given a mean value of 1·94 calories, which we may consider as the most accurate value, for the period between 1905 and 1924, with an average error which may be estimated at $\pm$ 0·02, allowing also for the small quantity of radiation in

the ultra-violet and infra-red which escapes measurement on account of the obstacles referred to.

Together with such precise determination of the solar constant, the problem has lately arisen of establishing whether, through causes inherent in the sun and its variable activity, this activity may be subject to variations of more or less long periodicity. The problem is difficult because of all the disturbing factors due to the terrestrial atmosphere.

Several investigators have occupied themselves with these researches, but the most extensive and prolonged investigations have been carried out by the Astrophysical Observatory of the Smithsonian Institution. According to these researches the values of the solar constant would seem to show certain variations in relation to the eleven-year cycle of solar activity, and other short-period variations.

As regards the first-mentioned variations, observations made at the purposely selected stations of Montezuma in Chile and Harqua Hala in Arizona, from 1920 to 1924, show that there was a considerable decrease in the annual average of the solar constant in 1922, which epoch corresponded to the minimum of solar activity. Then again, recent researches by Abbot on observations made at Mount Wilson from 1910 to 1920 show an undeniable correlation between the variation of the solar constant and the relative sunspot numbers, with an increase of 1 per cent of the solar constant in 1917, corresponding to this maximum sunspot period.

Fig. 150 shows the average results of observations carried out from 1922 to 1931 at three stations of the Smithsonian Institution, viz. Montezuma in Chile, Table Mountain in California, and Mt. Brukkaros (Africa), with a total variation of solar radiation of 1·5 per cent (the more rugged curve), compared with the curve of the relative numbers of sunspots for the same period.

On the other hand, Bernheimer and Marvin find in the monthly averages of the solar constant, deduced from observations made by the Smithsonian Institution, a direct relation to transmission coefficients determined at the same time. The trend of the monthly averages may be represented by a sine curve with a periodicity of one year, having its maximum in the summer and winter periods. Evidently the cause of this

periodicity must lie in the variability of the transmission coefficient and hence in the variability of the special conditions of the terrestrial atmosphere. Possibly this may be due to incomplete knowledge of the absorption caused by water vapour. However, the annual variations referred to cannot be influenced thereby, so we must conclude from the evidence of the observations that in all probability there are variations of the solar constant which follow the variations of the sun's eleven-year activity.

The difficulty of putting these slight variations of the solar constant in evidence for comparatively long periods becomes still greater when we try to establish the existence of variations

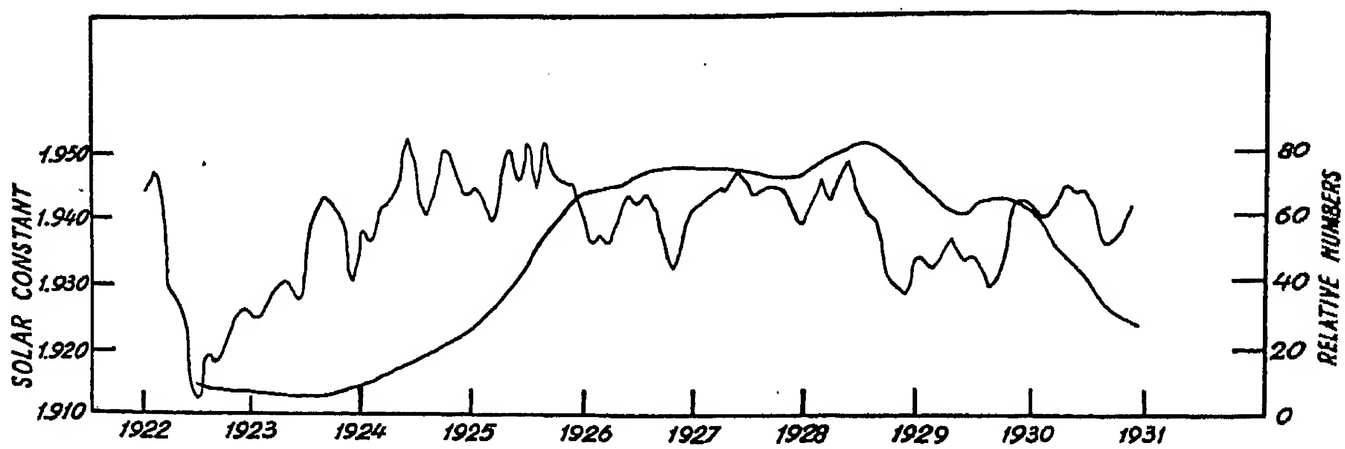

FIG. 150. Variation of solar radiation with time (Abbot).

taking place within short periods, e.g. from day to day. With the most precise present-day methods of observation and reduction and with stations selected in particularly favourable places so as to diminish the average errors, it has been found in recent years that the deviations of the results from an average value have become smaller and smaller, especially since the adoption of the pyranometer.

For the moment it may be said that the diurnal fluctuations observed average 0·012 gm cal cm^{-2} min^{-1}, viz. 0·60 per cent of the mean solar energy during one year, which variation is of an order of magnitude corresponding to the accuracy of pyranometric measurements. On the other hand we cannot rule out the possibility of there being short-period variations, especially under special conditions on the sun, as for instance during the passage of large spots across its central meridian.

Thus, Abbot believes he has established the fact that the smallest amplitudes of these short-period variations amount to 0·45 per cent and the largest to 2·5 per cent, and he furthermore considers them to be related to the trend of the temperatures and of the terrestrial barometric pressures (page 253).

According to Abbot, the longer periodicities are always due to agitation, in either an increasing or a decreasing sense, in the gaseous mass of the sun, as might be caused by agitating the incandescent mass in such a way that the radiation of the sun's interior can be more easily emitted. The short periodicities, which may last a few days, might on the other hand be due to special zones of increased radiation on the solar surface such as exist, for instance, in connection with faculae, flocculi or eruptions accompanying sunspots, or possibly to zones of diminished radiation, as on sunspots, where the gases are cooled down by expansion when they reach low-pressure levels.

It would not seem possible for the present to make a decisive statement on this complicated problem of the variations of solar radiation, even after the numerous measurements carried out by Pettit at Mount Wilson and in Arizona with an instrument of his own design.

Since these probable variations must take place in the violet region of the spectrum, Pettit tried to effect differential measurements of solar radiation by comparing a limited region of the spectrum at 3200 A with another region at 5000 A. A thermocouple receives solar radiation alternately through a silver film for the first region and through a gold film for the second; a galvanometer automatically registers the current variations at different hours of the day. Pettit thus obtains for each day of observation a curve depicting the ratio of the ultra-violet radiation and green radiation as a function of the mass of air traversed, which may be extrapolated for the sun at the zenith and for the limits of the terrestrial atmosphere.

The observations were commenced in 1924, and the variations of the ratio mentioned are interpreted as actual variations of ultra-violet solar radiation, taking constant intensity for green. As far as anything can be said for the short time that has elapsed since the commencement of these observations,

there would seem to be a proportionality between the variations observed and those of solar activity, in the sense that the ultra-violet radiation diminishes with the decrease of solar activity, and this proportionality is regularly published at Zürich in the bulletin giving the character figures of solar phenomena.

On the other hand Bernheimer, discussing observations by Pettit, proved that the monthly averages of ultra-violet radiation have a pronounced annual trend, with consequent higher values in winter and lower values in summer, so that attempts to relate the variations of ultra-violet radiation to the resulting variations of ozone in our atmosphere and to the trend of solar activity, would seem somewhat premature. It is calculated that if the first-mentioned variations were strictly due to the sun, the variations of the sun's temperature would be of the order of 1000°. Such variations would be noticeable in the spectrum of the reversing layer, which is not the case, so it seems more probable that the variations found in the region 3200 A are rather to be ascribed to the variability of conditions in our atmosphere.

Distribution of Energy in the Spectrum and on the Disc of the Sun

When investigating how the energy emitted by the sun is distributed over the different regions of its spectrum, we of course encounter the same difficulties as have been referred to above, which are caused by the terrestrial atmosphere.

With regard to the Fraunhofer lines, it is known how easily those belonging to the solar atmosphere can be separated from those of the terrestrial atmosphere by examining whether they are affected by the sun's rotation or not, but as regards the distribution of energy in the continuous spectrum and the limitation of the spectrum in the ultra-violet and infra-red, the problem is more difficult, and here again it is necessary to take bolograms at different altitudes of the sun above the horizon. In this way we obtain transmission coefficients for each individual region of the spectrum, from which the spectral energy is finally arrived at, as if it were observed outside the earth's atmosphere.

From Langley's measurements, reduced to normal spectrum, the solar energy is found to be distributed in the manner shown in Fig. 151. The considerable depressions noted in the ultra-red are all due to bands of water vapour and carbon dioxide.

In order to determine the energy of the solar spectrum it is necessary to allow for these depressions and also for the corrections in the extreme infra-red or ultra-violet which are partly due to ozone bands. The influence of these bands in the ultra-violet, which are particularly pronounced between 2900 A and 3150 A, has been studied by Fabry and Buisson and by other investigators, and would seem to be due to the presence in our atmosphere of a quantity of ozone equivalent to a layer 3 mm in thickness at atmospheric pressure.

Researches conducted to increase our knowledge of the solar

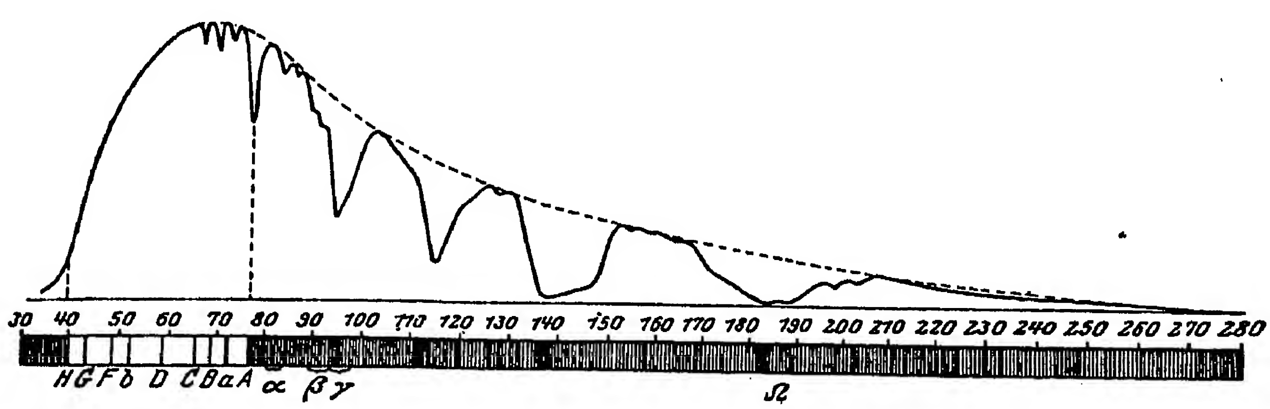

FIG. 151. Distribution of solar energy in the normal spectrum (Langley).

spectrum below 2900 A have not yet proved successful, again because of absorption by the high terrestrial atmosphere.

In the infra-red the spectrobolometric researches have been continued up to 53,000 A (5·3 microns), in which region there has also been found an absorption by the water vapour and carbon dioxide of our atmosphere.

The distribution of energy in the normal solar spectrum, as shown by the results of several investigators, is represented by the curve of Fig. 152. It can be seen that there is a very pronounced intensity maximum at 4700 A, with a decrease towards the larger wavelengths which is relatively slower than in the violet.

The theoretical curves for the distribution of energy calculated by Lindblad for an actual photosphere temperature of 5740°

and 6000° respectively, are indicated by the dotted lines in the figure. Other authors have also tried to deduce, from existing determinations, conclusions as to the temperature of the sun's external layers. We will discuss this after having dealt with the distribution of energy on the solar disc.

We have already stated (page 55) that this disc is not

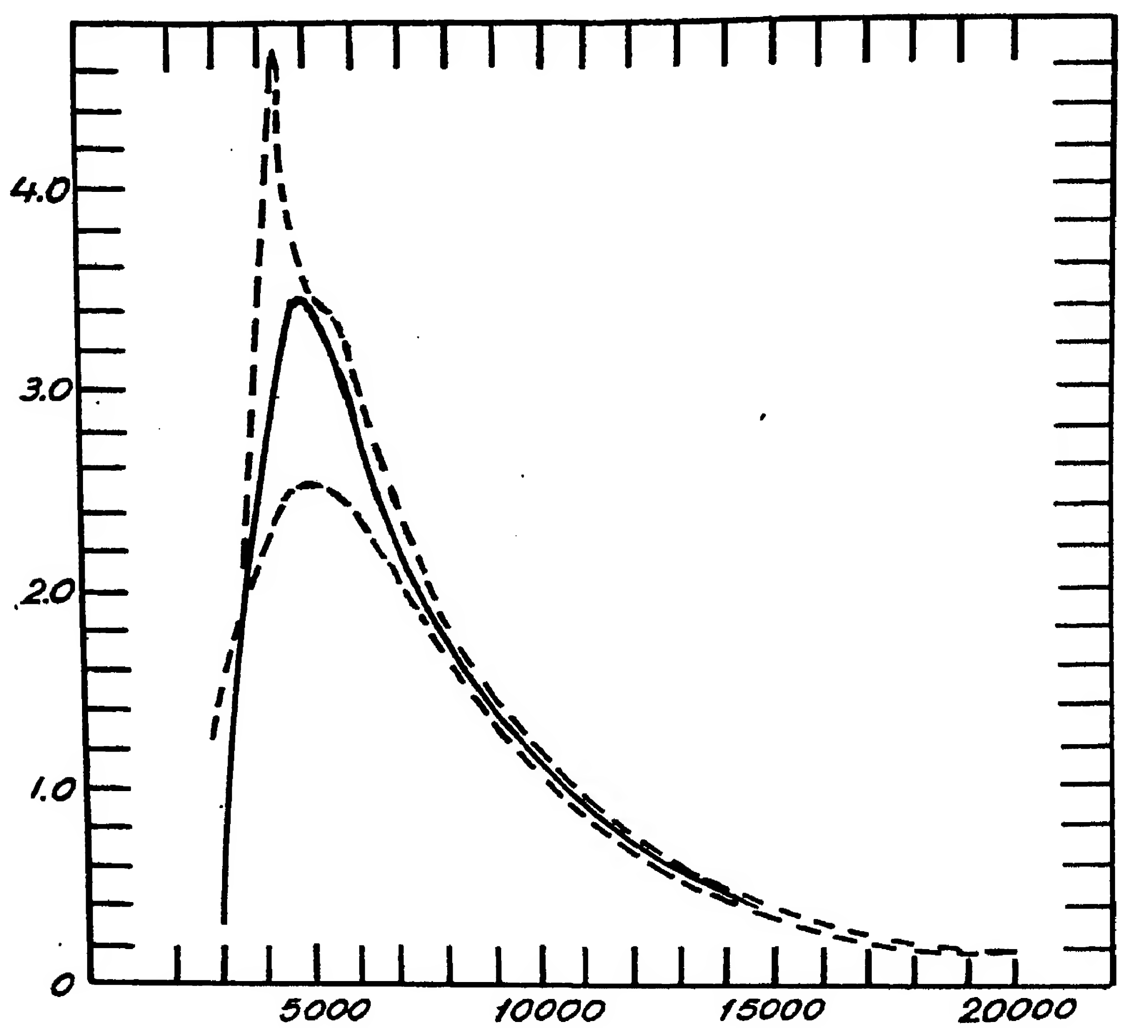

FIG. 152. Theoretical and experimental graphs of solar energy. (Abscissae: wavelength; ordinates: intensity).

uniformly illuminated but shows a rather rapid darkening towards the limb, as is well seen both visually and photographically, and that this must depend on the fact that at the limb the sun's atmosphere absorbs the rays more intensely than when they emerge perpendicularly at its surface. Since this absorption depends on wavelength, the degree of darkening at the limb obviously differs for the different wavelengths.

The sun being a gaseous sphere in radiative equilibrium, it

not only absorbs but also radiates with the same intensity, as has been proved by the theoretical researches of Schwarzschild and others when discussing the phenomenon of darkening at the solar limb. Moreover, on comparing the spectrum of the centre of the sun's disc with that of the limb, we must conclude that at the centre the rays emerge from hotter and deeper layers, whilst those at the limb emanate from cooler layers of high level. In other words, we can see more deeply into the solar atmosphere at the centre of the disc than at the limb, for

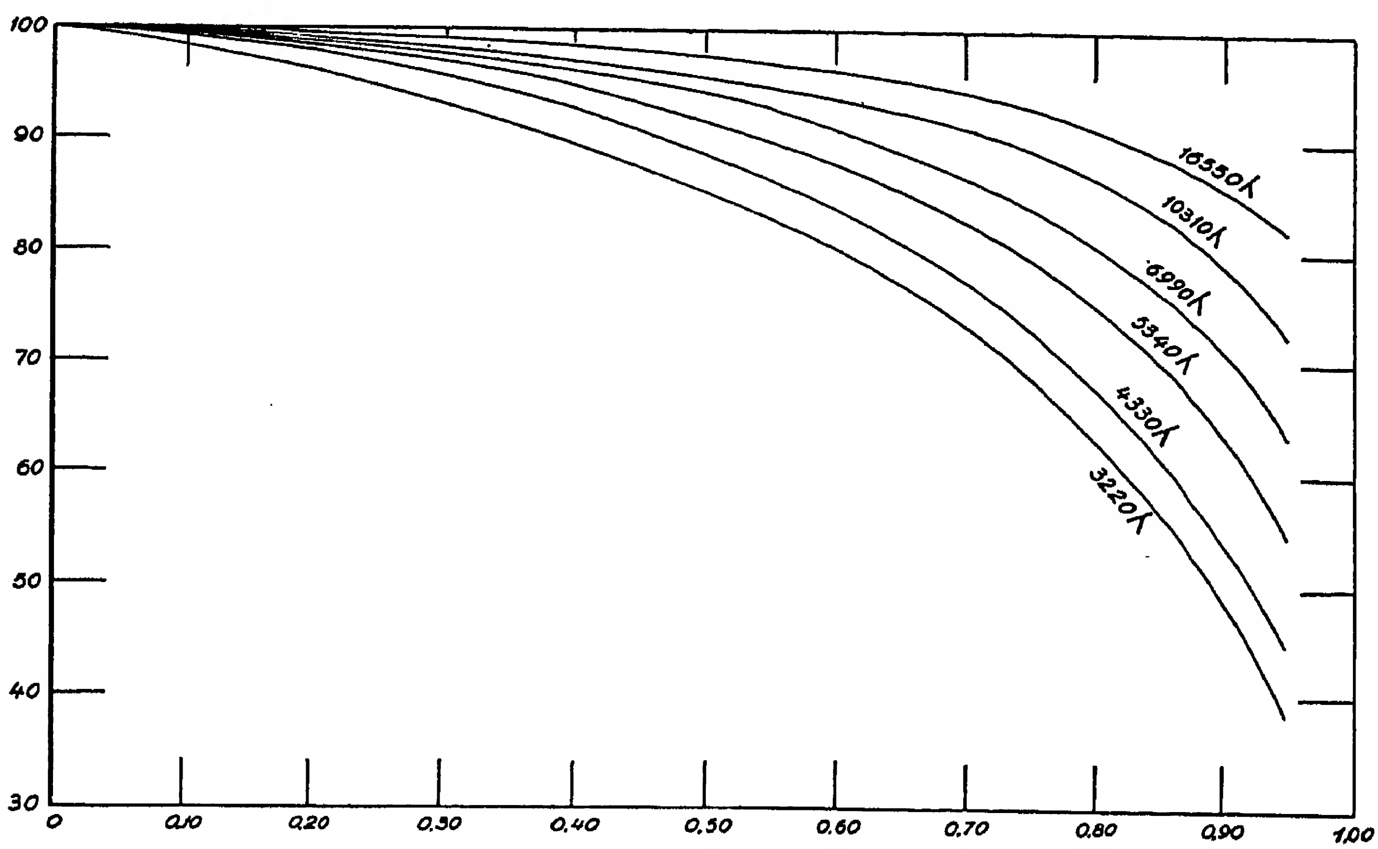

FIG. 153. Darkening at the sun's limb for different spectral regions (Abbot).

in the latter case we look obliquely into the sun's atmosphere and hence find deeper layers concealed by external layers of lower temperature and pressure.

Determinations of the total intensity of a limited region at the centre of the sun's disc and successively along one of its radii from the centre towards the limb, have already been carried out by early observers, using different methods. The results obtained do not agree very closely for various reasons, the principal being the differences in the instruments used

and the light dispersion in the terrestrial atmosphere, as a result of which the radiations of different solar regions are mixed. Nevertheless, it may be stated in general that if the intensity of radiation at the centre of the sun's disc is taken as 100, then the radiation at 0·50 from the centre drops to 93·4; at 0·75 it is 78·8, and at 0·98 it is 49·0, to become about 39 at the limb.

To diminish the dispersion effect, it occurred to Julius to make these observations during total eclipses of the sun and to ascertain the degree of darkening by carrying out intensity measurements at different points on the radius, the positions of these points depending on the amount of the sun's disc eclipsed by that of the moon. By this method Julius and others obtain more pronounced darkenings than are indicated above.

A better knowledge of the phenomenon of darkening at the limb is obtained when analogous determinations are made for different wavelengths. As early as 1872 Vogel determined the decrease of intensity from centre to limb of the sun's disc, and

AMOUNT OF DARKENING AT THE LIMB, ACCORDING TO ABBOT

$\frac{R}{\lambda}$	*0·00*	*0·40*	*0·75*	*0·95*
3220	144	129	99	49
4330	456	423	333	205
5340	463	440	366	254
6990	307	295	258	195
10,310	111	108	99	81
16,550	40	39	37	32
Wavelength of maximum energy	4580	4670	4780	5050

found this decrease to be more rapid in the spectral regions of shorter wavelength; later research by Schwarzschild and Villiger was continued in the ultra-violet up to 3000 A with the use of optical systems transparent to these radiations.

More extensive measurements have subsequently been

effected by Abbot, who made the solar image pass over the slit of a spectrobolometer and was thus able to register the energy received from a limited spectral region. The results of these measurements are indicated in Fig. 153, the intensity at the centre of the sun's disc (ordinates) being taken as 100 and the sun's radius (abscissae) as one. The table also gives the distribution of energy in the different spectral regions, but expressed in a uniform intensity scale for all wavelengths. The horizontal lines again depict the trend of the darkening at the limb for the different spectral regions, while the successive columns show, for a definite point on the solar radius from centre to limb, the distribution of energy in the normal spectrum outside our atmosphere.

From the table it can also be seen that the energy maxima are shifted towards the red the nearer we approach the limb. We shall see how these maxima may serve for determining the actual temperature of the photosphere in the different parts of the solar disc.

Although several theoretical researches have been conducted to account for the trend of darkening at the limb for different wavelengths, it must be acknowledged that up to the present it has not been possible to explain the real nature of the phenomenon.

According to some theories on the constitution of the sun (page 275), we should find in the direction east-west (i.e. at the solar equator) a darkening at the limb which is more pronounced than that along the axis of rotation. Researches by Abbot lead to the conclusion that if such a difference exists it must be so slight that it escapes our means of observation.

Minnaert has also determined, in the different spectral regions, the radius of the particular zone of the solar disc in which the prevailing radiation is equal to the mean radiation over the entire disc. He finds the constant value $R = 0 \cdot 75$ practically equal for all regions, from violet to red, with a slight increase up to $R = 0 \cdot 77$ towards the infra-red.

Temperature of the Photosphere and of Sunspots

The researches to which we have referred and which aim at ascertaining the solar constant, the distribution of energy

in the solar spectrum and the darkening at the limb, also tell us the temperature of the photosphere or at any rate give us a general approximate value, for it is evident from what we have stated that the emission of the photosphere must vary either in different wavelengths and at different points on the sun's disc, or according to whether we examine quiet or disturbed regions.

The approximate temperature may be calculated from results formerly obtained by applying well-known physical laws, viz. the "Stefan–Boltzmann law" and "Wien's law." The real temperature of the sun is generally understood to mean the temperature corresponding to a black body radiating an equal spectral intensity. As, however, the sun does not radiate like a black body, different values are obtained for the real temperature according to whether we take as basis the radiation of a particular spectral region or the shape of the energy curve.

The values of the "effective temperature" as determined in past years by several investigators are in the neighbourhood of 6000° absolute. From the Stefan–Boltzmann law, which says that the total energy radiated by a black body is proportional to the fourth power of its absolute temperature: $S = \sigma T^4$, we obtain by using the most recent values of the solar constant and of Stefan's constant σ:

$$\begin{aligned} S &= 1 \cdot 94 \text{ gm cal cm}^{-2} \text{ min}^{-1} \\ \sigma &= 1 \cdot 37 \,.\, 10^{-12} \text{ cal cm}^{-2} \text{ sec}^{-1} \text{ deg}^{-4}: \\ T &= 5770° \text{ absol.} \end{aligned}$$

From Wien's law, which says that the temperature multiplied by the wavelength of maximum intensity in the measured energy curve is equal to a constant:

$$T \times \lambda \max = C,$$

we obtain for $\lambda = 4740$ and $C = 288 \times 10^5$:

$$T = 6080° \text{ absol.}$$

The difference between the two results is considerable, and Milne, seeking to account for this difference, concludes that the intensity distribution in the sun, considered as a gaseous

sphere in a state of radiative equilibrium, corresponds to that of a black body with a shift towards the shorter wavelengths, so that its temperature, determined by the total radiation, is found to be lower than that given by Wien's law. The difference in question may also be considered due to the fact that, unlike separately observed spectral regions, the measurements of total radiation include radiations in the whole band of wavelengths originating from higher and therefore cooler layers of the photosphere.

There are also numerous researches on temperature of the

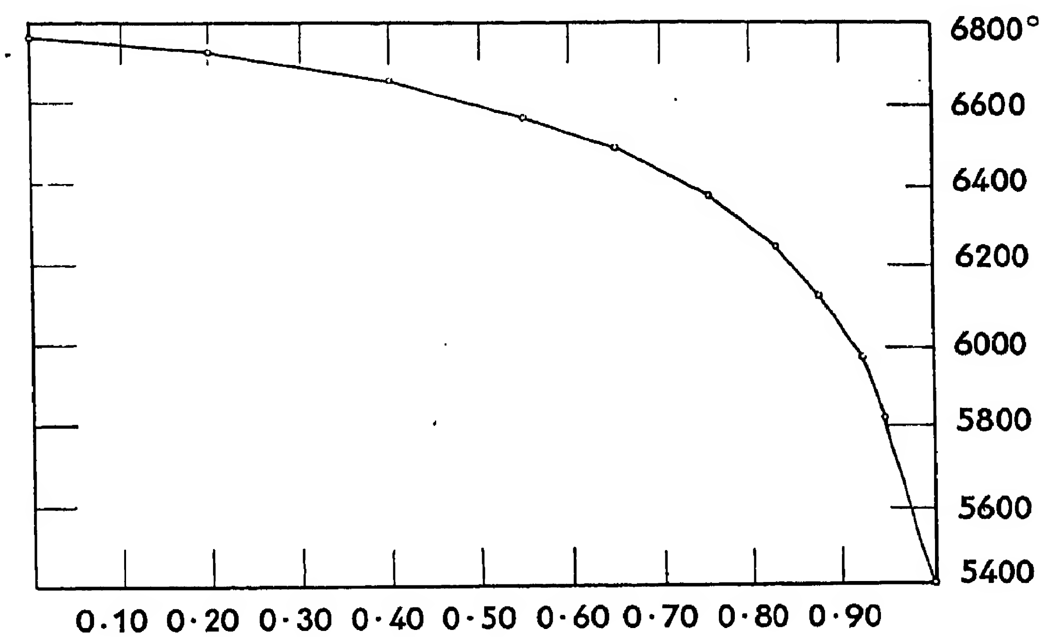

FIG. 154. Distribution of the mean temperature of the photosphere (Wilsing).

Abscissae: parts of the solar radius; ordinates: degrees absolute.

photosphere based on the application of Planck's equation of energy. This equation, which gives the energy of a radiating body for a specific wavelength as a function of the wavelength and of the absolute temperature, lends itself for determining this temperature when we know the energy radiated in the various wavelengths.

From Planck's equation, which is the most general formula and contains as particular cases those of Stefan–Boltzmann and Wien, we can calculate, for all spectral regions in which the energy radiated by the photosphere is measured, the corresponding temperatures, which would work out the same for all

regions, only if the photosphere were radiating like a black body. We have seen for the sun that this is only approximately true and that the observed energy distribution may be represented fairly well by the curve (Fig. 152, page 314) referring to a black body at 6000° or at any rate up to 5000 A. At the energy maxima the curve of the black body is considerably higher than that of the sun, and continues higher up to at least 3500 A. The infra-red shows a similar trend.

By this method we may conclude that the mean temperature of the photosphere is 5950° absolute, which is about the average of the two values previously determined. The real temperature of the individual layers naturally increases with increasing depth.

Wilsing, using the values obtained by Abbot (page 316) for the darkening at the limb, finds the temperature stated in Fig. 154 for different points on the disc, with a difference of about 1400° between the layers observed at the centre and those at the limb. As we have seen, the wavelength of maximum energy increases continually from the centre to the limb, so that according to Wien's law the temperature decreases from centre to limb. The rays from the limb, following an oblique path to reach the earth, are effaced by diffusion in the gas before attaining the same radial depth as the rays emerging radially from the centre.

The darkening at the limb, as already stated (page 316), is greater for violet than for red, either because the decrease of temperature causes a greater decrease of radiation for rays of shorter wavelength or because the molecular diffusion is greater for violet rays than for red rays, so that in the solar limb the actual radiating layer for the violet will be higher above the photosphere than the layer for red. The reversing layer is thus relatively cooler at the limb than at the centre.

The theory of ionization, too, enables us to establish the sun's temperature in the scale of temperature of fixed stars, which can be determined from the maximum intensity of the absorption lines in their spectra. Hence, from an examination of the spectrum of sunspots and faculae—always on the basis of the ionization theory—we may again conclude that the former have a lower and the latter a higher temperature than the photosphere.

Similarly, by taking the ionization theory as basis, a new method has recently been developed by Woolley for precise evaluation of the sun's temperature on the strength of observations carried out by him at Cambridge on the intensity of the line *Ca* I, 4227 A and *Ca* II, 3933 A (line K). From the width of these lines he obtains the ratio of the ionized calcium atoms to the neutral lines per cubic centimetre at a certain optical depth and, knowing the electron pressure, he infers a temperature of 6310° for integrated solar light over the entire disc; for the centre of the disc he finds 6690°.

On the other hand, from a study of the relative intensities of lines in solar and sunspot spectra—still using the theory of ionization—Russell finds that the temperature of the latter must lie between 4000° and 4500°.

By means of a thermocouple attached to a monochromator placed in the focal plane of the great tower of Mount Wilson, Pettit and Nicholson determined on various wavelengths the ratio between the intensity of sunspots and that of the photosphere. Multiplying this ratio by the energy curve of the centre of the sun's disc, they obtain a new energy curve in various wavelengths from $\lambda\ 0 \cdot 2\ \mu$ to $\lambda\ 2 \cdot 2\ \mu$, indicating a total energy corresponding to that of a black body at a temperature of 4860°. This value is also confirmed by measuring with a thermocouple the ratio between the total energy of the umbra of a sunspot and that of the photosphere. This ratio is found to be 0·47, which is in good agreement with the value calculated by comparing the surfaces embraced respectively by the energy curves of the spot and of the photosphere.

Recent researches conducted by Richardson at Mount Wilson on the lines due to carbon molecules, have led to a new determination of the temperature of the reversing layer and of sunspots. From comparison between the theoretical intensity and the intensity actually observed by him in the lines due to Swan bands (C_2), so called from the name of their discoverer, at 5165 A, and from the position of the maximum intensity of these bands, he calculates a temperature of 5700° for the reversing layer and of 4800° for the umbra of sunspots.

Summarizing the determinations mentioned, we obtain the table reproduced on the next page:

TEMPERATURES ON THE SUN

Method	*Solar Region*	*Absolute Temperature*
		°
Stefan-Boltzmann law . .	Reversing layer (entire disc)	5770
Wien's law	" "	6080
Planck's equation . .	" "	5950
Ionization of calcium . .	" "	6310
Wien's law	Reversing layer (centre of disc)	6760
	(solar limb)	5400
Ionization of calcium . .	(centre of disc)	6690
Thermocouple	Umbra of spots	4860
Intensity bands C_2 . .	Reversing layer (entire disc)	5700
	umbra of spots	4800

CHAPTER VII

THE SUN AMONG THE STARS

Comparison between the Physical Characteristics of the Sun and those of the Fixed Stars

Following up our exposition of the state of our knowledge of the sun, we may enquire whether the sun is to be considered as a star and what place it should be assigned in the classification and evolution of the stars, and once this is done we shall have established for at least one star a number of particulars and phenomena such as may reasonably be assumed to exist in different forms and under different aspects in all visible stars.

In order to form an idea of the magnitude and brightness of the sun as compared with other stars, it will be necessary to imagine it removed from its proximity to the earth and transported to a distance comparable to that of stars in the immediate vicinity of the solar system. As a matter of fact, in order to compare stars not only with the sun but also with each other, it is necessary to refer them to a standard distance and to determine, by means of their apparent magnitude, the magnitudes which they would acquire at that distance. We thus speak of the *absolute magnitude* of the star in contradistinction to the apparent magnitude, which is the brightness directly determined by means of photometers.

It is customary to adopt as absolute magnitude the magnitude which a star would possess if it were transported to the distance of 10 parsecs, viz. to such a distance as exhibits a parallax of $0 \cdot 1''$.

According to the most reliable measurements the visual apparent magnitude of the sun in the scale of magnitudes ordinarily employed for the stars, is $-26 \cdot 72$ (page 55), and the photographic magnitude $-25 \cdot 93$. With these numbers we calculate that the sun's absolute visual magnitude is $4 \cdot 85$ and its photographic magnitude $5 \cdot 64$. Thus transported to the distance of 10 parsecs, which is equivalent to $32 \cdot 6$ light-

years, the sun would become a star just brighter than the limit of stars visible to the naked eye (sixth magnitude).

By comparison with most known stars it may be stated that Sirius (*α Canis Maj.*) has a visual apparent magnitude of $-1 \cdot 6$. Knowing its distance from the solar system we can readily calculate its absolute magnitude, which is found to be $1 \cdot 3$. Passing from magnitude to brightness by the known ratio which connects these two quantities, we find that Sirius is twenty-seven times brighter than the sun (page 55). Rigel (*β Orionis*), which has a visual apparent magnitude of $0 \cdot 3$ but is much farther removed from the solar system of Sirius, has an absolute magnitude of $-5 \cdot 5$, so that it is 14,000 times brighter than the sun. On the other hand, Barnard's telescopic star, named after the discoverer of its relatively small distance from the solar system (parallax $= 0 \cdot 54''$), possesses an apparent magnitude of $9 \cdot 7$, and hence an absolute magnitude of $13 \cdot 3$, corresponding to a brightness only four ten-thousandths that of the sun.

From these numbers alone, which certainly cannot be regarded as limits, it may be concluded that the scale of brightnesses is very extensive, being (as far as we know at present) of the order of 21 magnitudes, representing a two hundred million-fold variation in intensity. On this vast scale we cannot say that the sun ranks among the faintest nor among the brightest of heavenly bodies, as it occupies an intermediate position; however, in terms of stellar evolution the sun may be said to belong to the category of so-called "dwarf" stars.

On the basis of the above-mentioned numbers, the difference between the photographic and the visual magnitude, or, as it is termed, the "colour index" of the sun, is found to be equal to $0 \cdot 79$, and this is in good agreement with the colour index of fixed stars whose spectral characteristics are similar to those of the sun; so the sun may be ranked among so-called yellow stars.

It is well known that, in the classification of spectral types established by Father Secchi in 1869, the second type is, as he states: "that of the yellow stars, like the Capella, Pollux, Arcturus, etc. The spectrum of these stars is like that of our sun, viz. composed of very thin, narrowly spaced lines occupying the same positions as those of the solar spectrum."

The most detailed and most recent classification in present use, viz. that of Draper, employs letters of the alphabet grouped as follows:

Classes	*Secchi's type colour*	
O, B, A, F	I	Bluish white
F, G, K	II	Yellow
K, M	III	Orange and red
R, N, S	IV	Red

These letters are accompanied by a number indicating the decimal division of each class; the sun is classified as G0 or somewhat further back, viz. in class F7.

The characteristics of the various classes forming a linear spectral sequence are given by the physical conditions of the stars belonging to it, viz. by the degree of excitation of the atoms in their atmosphere. In the stars of class O, most of the lines are produced by atoms with double or triple ionization, and even helium is ionized in spite of its high ionization potential. The degree of ionization decreases continuously in classes B and A, while in class F there begin to appear lines due to neutral atoms, which are more prevalent in classes G and K. In class M there are bands due to chemical compounds, and at the same time the ultimate lines of arc spectra, characteristic of low excitation, are intense; the same may be said of classes R, N and S.

The prevailing factor in the variation of these spectra is temperature, which is also responsible for the general colour of the star and hence also for its colour index. The fact may thus be established that the sun occupies a well-defined place in the spectral sequence of the stars, so that all stars round about class G must have the same physical characteristics of temperature and pressure at their surface as are found on the sun.

As to dimensions, very many stars are of about the same size as the sun and are also of roughly the same mass and density, while others are either much smaller or much larger. Barnard's star to which we have already referred, a red star with a temperature of 3000°, has a radius $R = 0{\cdot}2$ and a mass $M = 0{\cdot}2$ as compared with unity in each case for the

sun, while its density, taking that of water as unity, is $D = 45$. For Sirius, a bluish-white star with a temperature of 11,000°, we have $R = 2{\cdot}8$, $M = 2{\cdot}4$, $D = 0{\cdot}4$.

These two stars and the sun belong to what is termed *main sequence*, in stellar evolution, as understood nowadays, being composed entirely of dwarf stars in contrast to giant stars; the giants are yellow and red stars of much larger size. Among these is, for example, Capella (α *Aurigae*), which has the same spectrum as the sun and thus belongs to class G of the same temperature, with $R = 12$; $M = 4$; $D = 2 \times 10^{-3}$, and Antares (α *Scorpii*), a red star with a temperature of 3000° and with $R = 480$, $M = 30$, $D = 3 \times 10^{-7}$. The large size of these two stars and of the others belonging to the same class are, as can be gathered from these numbers, due to their low density rather than to the quantity of matter they contain.

Within the scheme of giant and dwarf stars we have a survey of all the different phases a star may assume, enabling us to classify each star correctly so as to understand its evolution and hence the present state of the sun.

It is generally believed nowadays that a single star may assume almost all known spectral types, starting from the condition of a giant star of huge mass and passing through the various phases with increasing temperature, reaching the main sequence in class B (bluish-white stars) and descending from this class to, say, class M, becoming denser and denser through contraction and cooling. According to this hypothesis the sun may once have been of the same mass, brightness and temperature as Sirius, and still earlier it may have been as much a giant as Capella. In the far distant future it may contract to a red dwarf, as faint as Barnard's star.

The time-scale formed by this conception of stellar evolution, as calculated by Russell, extends over a vast compass. Even allowing for the fact that radiation was necessarily more rapid when the mass was greater, the time required by the sun to attain its present mass after having had twice as great a mass, is found to be 5×10^{12} years. In order to attain a mass half as great as at present the sun would require a further period of 4×10^{13} years, and a period twenty times longer in order to attain one-fifth of its present mass.

The fact that the sun has continually been radiating the same amount of energy which we measure nowadays, is apparent from the geological history of the earth. The temperature of the earth's surface is maintained almost entirely by solar radiation. If what we call the solar constant had been different or had changed considerably, every form of life would in course of time have disappeared from the earth, owing either to excessive heat or to excessive cold. But geology and the fossils found on the earth tell us that from pre-Cambrian times a regular trend of organic evolution has been going on uninterruptedly. It must therefore be acknowledged that during this period, which may be estimated at several hundred million years, the sun has been sending on to the earth the same amount of energy as we are able to observe to-day.

It may also be enquired what position the sun occupies among the stars and what was its origin. This origin must evidently have been the same as that of the stars surrounding it in its immediate vicinity, since the identity of the sun with a certain class of very numerous stars has been established.

The sun is immersed in the Milky Way, an organic stellar system which, as is well known, crosses the heavens almost in a great circle. The Milky Way is composed of stars of all spectral types referred to in the foregoing and consists of cosmic material visible as bright or dark nebulae. Around the great circle, which constitutes the fundamental plane of the Galaxy, the stars of the various types crowd together, the majority of them belonging to classes O and B, then come open star-clusters, new stars, Cepheid variables, and gaseous nebulae. Globular star-clusters and spiral nebulae are more numerous in the parts farthest away from the principal plane of the Galaxy. The region of the space occupied and bounded by globular clusters seems to coincide approximately with that occupied by the Galactic system.

In former times it was believed, on the authority of Herschel and Kapteyn, that the centre of the Galactic system must be in the vicinity of the sun, but recent researches displace it from the centre and indicate it as being situated in the extensive stellar cloud formed by the constellations of Ophiuchus and Scorpius, about 50,000 light-years from the sun. If we plot in a diagram the position of known star-clusters as if they were

seen by an observer situated in space at a pole of the Galaxy, the sun would occupy the position indicated in Fig. 155, where the radius of the circle is equivalent to a distance of 125,000 light-years.

The sun in its eccentric position seems to form part of what Shapley calls the "local system," formed by bright stars surrounding it. This local system has the same elongated and crushed form as the main system, but is much smaller; it does not lie exactly in the plane of the Milky Way but is inclined to it at about 12°; the sun seems to be situated very near the principal plane of the Galaxy, at about 100 light-years to the north of it (Fig. 156).

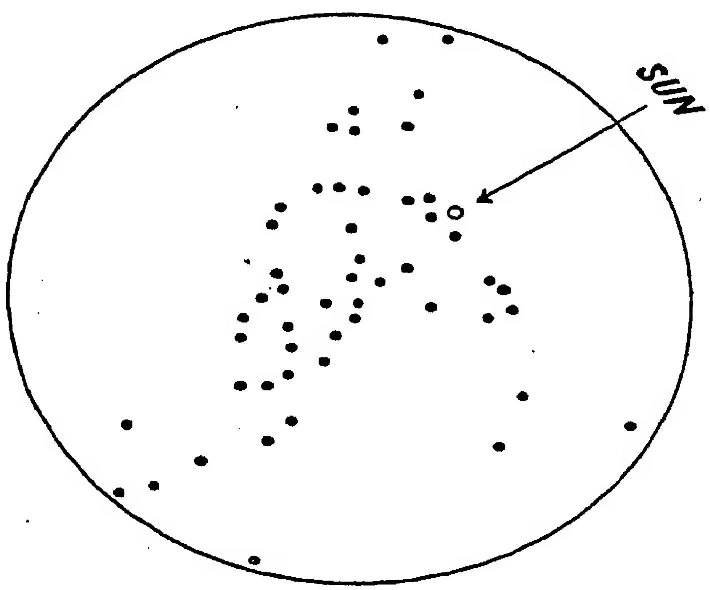

FIG. 155. Distribution of globular clusters (Shapley).

According to recent researches of Oort, Plaskett, Lindblad and others, the whole Galactic system seems to be in a state of rotation analogous to that of the planets around the sun, viz. its inner parts turn more rapidly than the outer ones. The axis of this gigantic wheel is situated just towards the centre of the Galaxy and hence at the centre of the system of globular clusters. In the neighbourhood of the sun the Galactic wheel makes a complete revolution in a period of about 230 million years, which implies for all stars in the vicinity of the sun a velocity of more than 300 km/sec, due solely to the rotation of the Galaxy.

From theoretical considerations on the formation and radiation of the stars, Jeans sets the higher limit of the sun's age at 8×10^{12} years. This remote antiquity goes back to the time when, according to our present line of thought, the sun was a primordial nebula of very low density from which, as evidenced in so many extra-Galactic nebulae in different phases of evolution which are visible in the heavens, numerous condensations have been separated as a result of gravitational

instability. These condensations are all the heavier the more tenuous the original gas was, and may attain a mass of a million times that of the sun. During contraction of the stellar body the condensations increase so much in density that, when their rotation causes an emission of gaseous matter, this matter inevitably becomes condensed into masses of the order

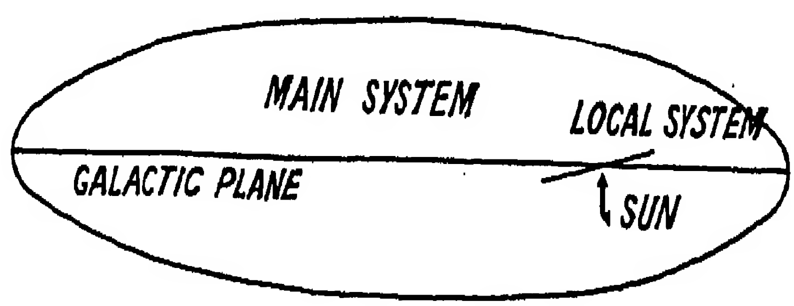

FIG. 156. Transverse section of the Milky Way.

of the stellar mass, viz. into stellar nuclei composed of single or multiple stars.

The sun, too, might have been formed in the manner indicated by this hypothesis, in which case the local system of which we have spoken might represent one of the condensed masses emitted by the primordial nebula. It is evident that the local system depends on and forms one with the Milky Way; the uncertain boundaries of this cloud of stars probably becomes merged little by little into the general Galactic field.

CHAPTER VIII

THE SUN AND THE EARTH

Relationships between Solar and Terrestrial Phenomena

The study of the effects, continuous in some cases and sporadic in others, of the various solar phenomena upon terrestrial phenomena, may be said to have commenced in 1850, when it was discovered almost at the same time by Wolf in Switzerland, Gautier in France, Lamont in Germany, and Sabine in England that terrestrial magnetism exhibits an eleven-year cycle corresponding with the eleven-year cycle of solar activity.

Although terrestrial phenomena belong to the domain of geophysics, it is of interest in connection with the constitution of the sun to enquire in what way its influence may be propagated, and under what conditions and with what velocity the sun transmits the influence which is responsible for terrestrial manifestations, whether of magnetic or other character.

From 1850 to the present day this question has been the object of experimental and theoretical researches and our knowledge of this important problem has greatly increased, especially as regards possible developments to which it might lead in the happenings of everyday life. In order to coordinate these researches an international commission was appointed in 1924, consisting of persons versed in the study of solar physics, geophysics, meteorology, radiotelegraphy, etc.

The principal terrestrial phenomena which are known with certainty to depend on intrinsic variations in the state of the sun or on variations in its position with respect to the earth, are: (1) magnetic fields on the earth and electric currents in the terrestrial atmosphere, (2) polar aurorae, (3) meteorological phenomena.

Other classes of phenomena which are probably dependent on solar variations, are: (4) atmospheric electricity (potential gradient and ionization of the atmosphere), (5) radio trans-

missions, (6) quantity of ozone in the upper atmosphere, (7) auroral extra-polar light, (8) atmospheric absorption at high levels, (9) penetrating radiation, and (10) light of the night sky.

On the other hand, the principal variable phenomena on the sun which certainly influence terrestrial conditions are: (1) the general radiation of the sun, (2) local disturbances on the sun which manifest themselves as spots, faculae and prominences, (3) the general trend of the solar cycle.

Other phenomena which, like those already mentioned, may be of influence on the earth but require further investigation, are: (4) solar disturbances which manifest themselves in intense local magnetic fields, (5) changes in the magnetic polarity of sunspots for each eleven-year cycle, (6) corpuscles emitted by the sun, as indicated by prominences and by the corona.

While it is true that we observe on the sun several classes of activity corresponding to certain terrestrial phenomena, it is also true that other terrestrial phenomena are known for which no counterpart can be traced on the sun. It remains to be seen whether it will be possible, with the means at present available or with future resources, to discover any other classes of terrestrial phenomena associated with solar activity.

Up to a few years ago the only disturbances that could be observed on the sun were spots and faculae, which from the times of Galileo have been described and recorded on the solar disc. At a later date Wolf's relative numbers were available, and for more precise valuation the area covered by sunspots and by faculae on the sun's surface was mapped out (page 68).

Since means were discovered for spectroscopic observation of prominences on the solar limb in full sunlight (page 137) another important indication of chromospheric activity is furnished by observing the frequency and extent of prominences. In this way a continuous series of these observations has been collected from 1869 onwards, first only visually and later also photographically. Finally, the invention of the spectroheliograph permitted observations as to the distribution of hydrogen and calcium in the solar chromosphere, which distribution, as we have seen, varies considerably according

to the conditions of greater or lesser activity of the sun. These observations revealed disturbed zones and eruptions that are not directly visible, and they therefore greatly enlarge our possibilities of investigating solar phenomena.

The elaboration of all these data gathered from solar observations is a laborious and lengthy task, not to speak of the difficulty of evaluating the intensity of the phenomena in a homogeneous scale. There having been for some time past a bulletin stating daily, in an empirical and approximate scale, the condition of terrestrial magnetism and its variations, a proposal was made to astronomers at the meeting of the International Union held at Leyden in 1928 to study ways and means of giving reliable periodical information on the condition of solar activity. It was decided to publish quarterly a bulletin of character figures of the solar phenomena to which we have already referred (page 125).

The bulletin publishes quarterly: (1) Wolf's sunspot relative numbers, (2) the character figures for calcium flocculi, (3) and (4) the character figures for the bright and dark hydrogen flocculi. The bright hydrogen flocculi are kept separate from the dark ones, since the two phenomena are different in frequency and distribution.

Observations with the spectrohelioscope, which, as already stated (page 119), are complementary to those of the spectroheliograph, have of late also been collected in the Zürich Bulletin, so it may now be said that a fairly continual and systematic supervision of the phenomena developing on the sun has been achieved.

From 1924 onwards the bulletin also gives the intensity of ultra-violet radiation, which is determined daily at Mount Wilson by Pettit's method (page 311), although it is not yet quite certain which part is due to variations in the transparency of the terrestrial atmosphere.

Having dealt with the information we may gather from the sun, we will now see what parallel phenomena may be recorded on the earth. The dependency of the variations of terrestrial magnetism on the eleven-year cycle of the sun would be sufficient of itself to give an indication for the development of solar activity, but there is more: The diurnal and annual variations of terrestrial magnetism are evidently connected

with solar radiation, which reaches the earth in a variable manner both during the day and in the course of the year. Moreover, the so-called "magnetic storms," viz. the rapid and irregular variations of the earth's magnetic field, also seem in most cases to be directly dependent on considerable disturbances on the sun's disc.

It is known that the ultra-violet radiation of the sun is principally absorbed by ozone in the higher regions of the terrestrial atmosphere, and if this radiation is the cause of ionization the ozone itself must be the ionized constituent. Whereas this process may explain the diurnal and annual variation of terrestrial magnetism, a great increase of ultra-violet radiation is improbable at the maximum of solar activity. It would therefore seem as if corpuscular radiation from the sun is the cause of ionization, but up to the present we have no certain proof that any such corpuscular radiation exists.

A study of the irregular variations of terrestrial magnetism indicates that there is not only ionization in certain special regions but that, especially in high latitudes, the conductivity of the air periodically increases. This increase of conductivity occurs both in the illuminated hemisphere and in the dark one, and when the increase is considerable we have manifestations of polar aurorae. The position of these aurorae and their connection with disturbances noted on the earth's surface, show that they must originate in electrically charged corpuscular radiation emitted by the sun. This radiation is deflected towards the polar regions by the terrestrial magnetic field.

The lower limit of the height of the aurora, about 90 km, thus represents the limit of penetration of the solar corpuscles; their nature and the sign of the electric charge are unknown at present. It may be assumed that they are swiftly-moving electrons or, what is more probable, that the stream of corpuscles consists of ions of opposite charge in almost equal numbers. The emission of such a current agrees with the knowledge that has been gathered of the constitution and equilibrium of the solar atmosphere. In the disturbed regions the equilibrium is destroyed, swarms of ions are expelled by radiation pressure and attain a velocity sufficient to carry them beyond the limits of the solar atmosphere.

In accordance with Milne's theory (page 273) it is possible that, from time to time, atoms which have attained great heights are projected outside the solar atmosphere by radiation pressure. Their speed of escape from the gravitational field of the sun has a well-defined limit which Milne calculates to be approximately 1,600 km/sec for ionized calcium atoms; at this speed they would be capable of penetrating the earth's atmosphere. The magnitude of this limiting velocity is the same for atoms of other elements too, for instance *H*, *He*, *Ti*II, *Sr*II, *Mg* and any other element which is held in suspension in the chromosphere by radiation pressure.

If it were possible to trace the exact origin of the emission of corpuscles likely to reach the earth's atmosphere we should of course have a better idea of the development of the phenomenon or at least be able to ascertain the transmission time. It has repeatedly been noticed that violent magnetic storms take place when large spots are visible on the sun's surface, and the connection between the two phenomena has been discussed at length by various authors.

Maunder, considering the observations carried out at Greenwich between 1875 and 1903, identified 19 magnetic storms connected with the presence of sunspots. These storms took place at about a time when spots (or rather, groups of spots) having an area of at least one-thousandth of the solar disc were crossing the central meridian of the sun. Between September 1898 and October 1903, when there were no large sunspots, no violent magnetic storms occurred. But when, in October 1903, a large group of spots appeared after five years, it was accompanied by a magnetic storm of very great intensity. The seven most intense storms noted by Maunder during the period of twenty-nine years referred to above, took place when seven of the largest groups of sunspots were visible.

It should not be thought, however, that the area of a group of spots can furnish an exact measure for the intensity of the corresponding magnetic storm. Thus, for example, on October 12, 1903, the central meridian of the sun was traversed by a very large group of spots covering a length of eighteen terrestrial diameters (about 230,000 km) accompanied by a magnetic storm for which the magnetic needle showed an oscillation from 30′ to 60′. On October 31st of the same year

another group of spots traversed the solar meridian, this group covering less than one-third the area of the previous one, but the magnetic storm caused thereby was considerably more violent, being the greatest registered at Greenwich during the time interval concerned.

If we assume that great magnetic storms take place simultaneously with the occurrence of large spots, we further find from Maunder's researches that they commence during an interval between 34 hours before the passage of a group of spots across the central meridian of the sun and 86 hours after such passage, or, to express it in degrees of longitude, between 20° east and 48° west of the central meridian; on an average terrestrial storms commence 26 hours after the spots or group of spots has crossed the central meridian of the sun.

It would thus seem that there exists on the sun's disc a well-defined zone of preference from which the phenomenon may emanate. In cases where disturbances of terrestrial magnetism were recorded as soon as the spots appeared at the sun's eastern limb and lasted until they disappeared at its western limb, more violent disturbances were noticed after the spots had passed across the central meridian.

If magnetic disturbances on the earth are due to clouds of corpuscles which are projected from definite regions surrounding the spots, it is evident that they cannot reach the earth until the regions in question are conveniently placed with respect to the earth, i.e. at favourable angles with the line joining the centre of the earth to that of the sun, which angles may be deduced from Maunder's determinations. These angles would seldom exceed 34° longitude, because the interval of 120 hours during which the storms may take place corresponds to a total angle of 68°. Assuming the mean western position of the spot at the commencement of a magnetic storm, i.e. 26 hours to the west of the meridian, this will be the transmission time taken by the corpuscles to traverse the distance sun-earth with possible maximum inclinations of 34° to the east or to the west of the line of sight.

From these considerations it thus seems that the swarms of corpuscles may be emitted by the spots or by the neighbouring regions in any direction, within the limits of a cone whose

apex of about 68° is situated in the spot, the axis being in the direction of a solar radius, at a mean velocity of 1600 km/sec. This velocity agrees exactly with that found theoretically by Milne (page 334).

Riccò considers the fact that the intensity of terrestrial disturbance gradually increases according as the spot comes into a more favourable position for the emission of the swarms of corpuscles directed towards the earth. To this end he compares the intensity of the maximum of disturbance with the moment at which the spot crosses the central meridian of the sun, viz. the moment at which it is nearer to the line joining the centres of sun and earth. From observational material discussed by Maunder and from other typical phenomena like the great magnetic storm of September 25, 1909, which occurred simultaneously with the occurrence of a large spot, he calculates a time of 40 to 50 hours for propagation from the sun to the earth of the solar influence on terrestrial magnetism, viz. a velocity of from 900 to 1000 km/sec.

The fact that there is no exact agreement between the occurrence, size and position of sunspots and the magnetic disturbances of the earth, would seem to indicate that, as already suggested by Tacchini and subsequently confirmed by Hale, the origin of these disturbances is rather to be sought in eruptions, which can be seen by the spectroheliograph and spectrohelioscope and are usually found in regions in the neighbourhood of sunspots. This hypothesis is confirmed by the fact that the solar areas which influence terrestrial magnetism sometimes have no spots or only come into evidence after a spot has disappeared, to be repeated at intervals equal to the period of solar rotation.

It will be understood how difficult it is to follow, by visual and photographic observations, the complete development of a given eruption and the moment corresponding to the maximum activity from which we may expect the maximum of magnetic disturbance, but in recent years the more extensive use of the spectroheliograph has enabled us to observe some typical cases in which the conditions stated have been established.

On July 15, 1892, Hale succeeded in photographing with

the spectroheliograph an eruption of exceptional brightness which varied very rapidly in form and intensity. According to the examination made of it by W. J. S. Lockyer, the interval elapsing from the moment of maximum activity of the solar eruption to the commencement of the magnetic storm and to the moment of maximum activity was respectively 21 h. 3 m. and 25 h. 3 m.

Another solar eruption the entire course of which seems to have been followed and which caused two spots situated in opposite hemispheres to become associated with extensive masses of hydrogen and calcium, was the one observed by Fox and by myself on September 10, 1908, with the Rumford spectroheliograph attached to the 40-inch refractor of the Yerkes Observatory. The whole phenomenon lasted less than four hours, and the time elapsing between its maximum intensity and the commencement of a great magnetic storm recorded on the earth was 26 hours. The maximum intensity of this storm was registered 43 hours after that of the solar eruption. In this eruption Doppler shifts were measured in the $H\alpha$ line, due to hydrogen descending on the sun's surface at a velocity of 100 to 200 km/sec.

On September 24, 1909, spectroheliograms taken at South Kensington with the K line of calcium on a very active group of spots showed the development of a considerable eruption. The solar phenomenon can be followed on those spectroheliograms and also on one obtained by Slocum at the Yerkes Observatory, and it may be concluded that, in the group of eastern spots then present on the sun, the maximum of the eruption was attained at about 10 h. 5 m. G.M.T., it being already on the decrease one hour later. An intense magnetic storm was registered on the earth, commencing 26 hours later and having its maximum 30 hours after the maximum activity of the solar eruption.

During the last maximum of activity other cases were recorded with the spectroheliograph and observed visually with the spectrohelioscope, by Hale. On February 22, 1926, Royds registered at Kodaikanal, in a series of spectroheliograms taken with the lines H and $K_{2,3}$, filaments and flocculi which were very much brighter than the ordinary flocculi over an active spot whose maximum development can be

established at about 14 h. 30 m. G.M.T. On February 23rd there was a terrestrial magnetic storm which commenced 23 h. 30 m. after the maximum of activity of the solar eruption and 50 h. 30 m. after attaining its own maximum of activity.

At the Meudon Observatory, D'Azambuja and Grenat obtained *Hα* spectroheliograms of a group of spots that crossed the meridian on October 15, 1926, on which date there was an eruption of exceptional intensity. In this case, too, the phenomenon seems to have been very rapid, its maximum having taken place at 13 h. 15 m. G.M.T. on October 13th. About an hour later, already in the decreasing phase, masses of hydrogen were observed descending on the sun with a velocity of the order of 130 km/sec. A violent magnetic storm commenced on the earth 31 hours later and attained its maximum intensity 56 hours after the eruption.

On January 24, 1926, Hale observed visually with the spectrohelioscope a great eruption on a vast group of spots, which was also followed by a magnetic storm and by a brilliant aurora. Of this observation there are, however, no complete data for determining the maximum development of the eruption. In future observers will undoubtedly be better able to establish the trend of these rapid and violent eruptions by means of the two instruments mentioned. To supplement these facts, regular observations have been made with the spectrohelioscope, especially at Greenwich by H. W. Newton, and in several other observatories well distributed in longitude.

Collecting the small number of eruptions which it has up to now been possible to observe and follow in a more or less continuous manner, we have the table on page 339.

Whilst there is a considerable margin of deviation in the 41 h. delay between maximum activity of the eruption and maximum intensity of the magnetic storm, owing possibly to the difficulty of establishing the latter for the various magnetic elements measured, the 25·6 h. delay in the commencement of the magnetic storm seems fairly precise, and is also in good agreement with the value already determined from the transit of the spot across the central meridian.

It would thus seem that the velocity of about 1,600 km/sec for transmission of the disturbance from the sun to the earth is sufficiently well established by this class of observations, and the

coincidence of the theoretical value with the observed value warrants the hypothesis that when an eruption occurs on the sun the disturbed regions cause an emission of atoms in swarms, with consequent disturbances in terrestrial magnetism when the direction of the swarms of atoms is such that they can reach the earth. This hypothesis is substantiated by yet another phenomenon, that of repetition of the magnetic storm at certain intervals. As a matter of fact it has been found that these storms have a tendency to recur after a complete solar rotation, as if there were magnetically active

Solar eruption	*Magnetic storm*	
Date and G.M.T. of maximum activity	*Commencement*	*Maximum*
	After the solar eruption	
	h.	*h.*
July 15, 1892, 5·7 h. ..	21·3	25·3
Sept. 10, 1908, 8·0 h. ..	26·0	43·0
Sept. 24, 1909, 10·6 h. ..	26·0	30·0
Feb. 22, 1926, 14·5 h. ..	23·5	50·5
Oct. 15, 1926, 13·2 h. ..	31·0	56·0
Average	25·6	41·0

areas on the sun before and after the formation of any visible phenomenon, such as a group of spots or some kind of eruption. It would thus seem that the appearance of spots, flocculi and eruptions is an important phase of activity of these areas, but that other phases of activity may precede or follow these specific phenomena without our being able to observe them either visually or photographically.

It must therefore be concluded that the sun's influence, of whatever nature it may be, is not transmitted uniformly in all directions and hence does not radiate like heat, but that its action is limited to one well-defined direction. This is also evident from the fact that the magnetic disturbances on the earth generally commence instantaneously all over the globe, which might be attributed to the impulse of an energetic wave radiating in all directions, from the sun as centre, if the

disturbances had no connection whatsoever with each other. But it is not possible to explain it when we observe that the phenomenon recurs after the lapse of exactly one or more periods of synodic rotation of the sun. So we must assume that the earth encounters from time to time a definite current which is continually fed from one and the same area of the sun's surface, when this area returns to a favourable position after a complete synodic rotation of the sun.

From magnetic observations alone we thus find that there must be certain disturbed and limited areas which may last longer than the life of sunspots, and which produce magnetic disturbances, with the probable emission of swarms of corpuscles. These disturbed areas often escape our present means of solar observation, their sole indication being the activity of terrestrial magnetism. Under this aspect the observation of magnetic activity becomes of astrophysical as well as geophysical importance, as it indicates the epochs during which the earth is actually under the influence of solar currents. We must therefore acknowledge the unsuitability, or rather the lack of sensitivity, of astronomical means to establish the presence of certain solar disturbances which nevertheless manifest themselves on the earth.

The problem of variation of the solar constant and of variation of ultra-violet radiation has not been solved, in so far as the means at present available do not tell us for certain how much of these variations is due to actual variations on the sun and how much to causes inherent in our atmosphere.

Then again, the phenomenon of polar aurorae—intimately associated, as already mentioned (page 333), with terrestrial magnetism—finds its explanation in the phenomena of solar activity. As is known, these aurorae occur with greater frequency in the polar zones. Around the north pole the zone of maximum frequency of the aurorae is bounded by a line starting from the North Cape and passing along the northern coasts of Nova Zembla, the extreme northerly point of Siberia, Hudson Bay, Labrador, the southern regions of Greenland, and Iceland. This zone thus contains the geographical and magnetic pole (as is also the case in the southern hemisphere), whilst at lower latitudes the phenomenon becomes increasingly rare. Tracing the frequency curve of the aurorae visible in these

regions, we find that it closely follows that of the eleven-year solar activity and that of terrestrial magnetism; moreover, magnetic storms are always accompanied by pronounced auroral phenomena.

On the occasion of the great polar aurora observed over the whole world in 1872, during the night of February 4th–5th, G. B. Donati was the first to state clearly that this phenomenon must be due to solar causes. The sun had passed through a very considerable period of its maximum activity two years previous to 1872 and was still in a state of great disturbance, as is confirmed by the large number of spots observed during that year. The aurora of February was observed in a large number of places all over the globe. Father Secchi has given an admirable description of this aurora in the meteorological bulletin of the Observatory of the Collegio Romano.

Donati, sending a circular letter to all the Italian consuls, gathered as much information as possible on the circumstances of the phenomenon, and in his memoir, which was the first and last he wrote at Arcetri before his premature decease, he discussed all the reasons which led him to believe that the aurora was of cosmic and possibly of solar origin. Comparing the times at which the aurora appeared in the different places, he thus concludes: "The luminous phenomena of the great polar aurora which was observed over a vast area of the earth during the night of February 4th–5th, 1872, were seen first in the east and then in the west, and manifested themselves at various points on the earth almost at the same hour of the place in question, but with a tendency to advance ahead of that hour according as they were propagated from east to west." It having thus been established that the appearance of the aurora was connected with the apparent path of the sun and that it could not therefore have a terrestrial meteorological origin, he affirms that the aid must be invoked of a new cosmic meteorology. "The phenomenon of sunspots," he says, "and all other phenomena occurring in the solar globe, are indeed outside the domain of old-time meteorology, and if aurorae are related to phenomena occurring in the sun, we would be inclined to say that the latter are due not only to actual meteorological causes, but also to cosmic causes."

After Donati's time, the cosmic origin of aurorae having

since been recognized beyond all doubt, many observations and experiments were carried out and theories propounded to explain their formation. This was especially the case in Norway, where, as already stated, aurorae can be observed with greater frequency, photographs of them being taken from different points with a view to determining their height and examining their emission spectra.

In 1896 Birkeland finds that a magnetic pole acting as a lens on a parallel ray of light, forces a beam of cathode rays to condense on one point. He therefore thinks that the aurora is due to such an influence acting in the terrestrial magnetic field on cathode rays coming from the sun. By experimental tests and by using a spherical electromagnet placed under the influence of a beam of cathode rays, he was able to imitate the principal phenomena of the aurora.

Störmer, who has carried out extensive theoretical researches and experimented much on this question, assumed that the movements of the earth and sun are negligible and that the terrestrial magnetic field is like that of a uniformly magnetized sphere, and by this line of reasoning he succeeded in calculating the trajectory of electric corpuscles emanating from the sun. The results of this calculation were so satisfactory that, successfully continuing his researches, he studied the trajectories of both positively and negatively charged particles travelling at different velocities. In this way he was able to explain the observed appearances and heights of the aurorae, the latitude of the zones of maximum frequency, and why those extending down to comparatively low latitudes are always accompanied by magnetic storms. According to Störmer's theory, the cathode rays from the sun bend around the earth when still far distant from it and thus approach the polar regions, producing aurorae on the side of the globe not illuminated by the sun, while many other trajectories encounter the earth in a similar fashion, especially in the Antarctic regions.

Concluding, it may be stated that the sun certainly does emit corpuscles into space which consist, in the part already investigated, of electrons travelling at a high velocity, but which probably also contain corpuscles of other kinds. This emission is intimately connected with the general and local

activity of the sun and manifests itself to us by the phenomena of magnetic storms and polar aurorae. When the prolonged observation of solar phenomena and terrestrial magnetism has been better organized, as is being done, it will be possible to find out more about the sun's corpuscular radiation.

We have not yet dealt with the dependence of radio transmissions and meteorological and climatological variations on solar phenomena.

In recent years much work has been done on radiotelegraphic transmissions with increasingly precise instruments, continual observations being made to establish a correlation between solar activity and terrestrial magnetism on the one hand, and the propagation of radio waves and atmospheric disturbances on the other hand. It can be positively affirmed that such a correlation must indeed exist. We can now say that in the present cycle (1934–1945), near the maximum of solar activity (1937–38), the correlation between solar eruptions and fadings seems very evident and conclusive.

Some uncertainty arises on account of the difference in behaviour between radio waves of different wavelengths under the influence of magnetic storms. According to Appleton the increase of signal strength which is observed on long waves (above 10,000 metres) under the influence of these storms is due to increased ionization of the Kennelly–Heaviside layer at these moments, the long waves being thrown back to earth through some kind of reflection which increases their intensity when the degree of ionization becomes greater. Short waves, on the other hand, are found to be attenuated on account of increased ionization, because they penetrate the layer to a greater depth and are absorbed to a greater extent.

In terrestrial meteorology the solar influence which certainly must exist is manifested in such a complicated manner that we cannot yet say much regarding any correlation between the two. It is certain that the sun's vicissitudes and the phenomena of the earth's atmosphere do not show any clear and obvious agreement during the eleven-year period of solar activity, and analysis of the data collected during concurrent individual periods and during groups of periods, shows that there are indeed periods of cycles, but that they vary in amplitude and are occasionally opposite in phase. No reason-

able explanation has up to now been found to account for these facts, which differ in the different regions of the earth and may represent opposite effects according to the geographical position of the regions concerned. It is indeed very difficult to foresee what influence the increase of solar activity may have on the weather in a certain place; as a rule it is assumed that the temperature must rise in some areas and fall in others, but this again may be subject to seasonal variations.

The general circulation of the atmosphere is undoubtedly intensified by this fact, but what variations it may produce, for example, in the distribution of pressure and rainfall cannot be concluded as yet. It is not certain, either, that an increase of solar radiation reaching the earth's surface would produce greater radiation thereon, because the higher strata of the atmosphere may at the same time become more opaque and hence transmit a lesser quantity of radiation. Hence, although evidence shows that the variations of temperature of the earth must depend on variations of solar activity, it must nevertheless be concluded that the variations of solar radiation are not the direct cause of the variation of meteorological factors on the earth.

Efforts are being made to establish numerous other relationships, considering for example the area of glaciers in the polar basins in relation to the number of sunspots, the variations of pressure, the amount of rainfall, the annual growth of trees, the levels of the great lakes, floods, and other terrestrial phenomena.

Recent studies of sections of the trunks of very old trees, especially the studies carried out by Douglass in different parts of the world, furnish evidence of an eleven-year period in the concentric rings of their annual growth, or rather, of double this period, which, as we have seen, would be just the complete period of solar activity, taking into account the polarity reversal of the spots (page 214). The cycle, in the sections of tree trunks, manifests itself in an increase of growth during sunspot maxima, as can be seen by the two sections (Fig. 157) of trees grown near the Baltic.

The frequency maxima of the spots of 1830, 1837, 1848, 1871, 1884, 1895 and 1905 are marked as black dots. But here again the superposition of other cycles renders it difficult to

establish a general and certain rule, although it may be foreseen that later researches will give further important results.

In the case of the great African lakes: Nyassa, Victoria, Albert, there would seem to be evidence that their level rises as sunspots increase in number and falls as they decrease.

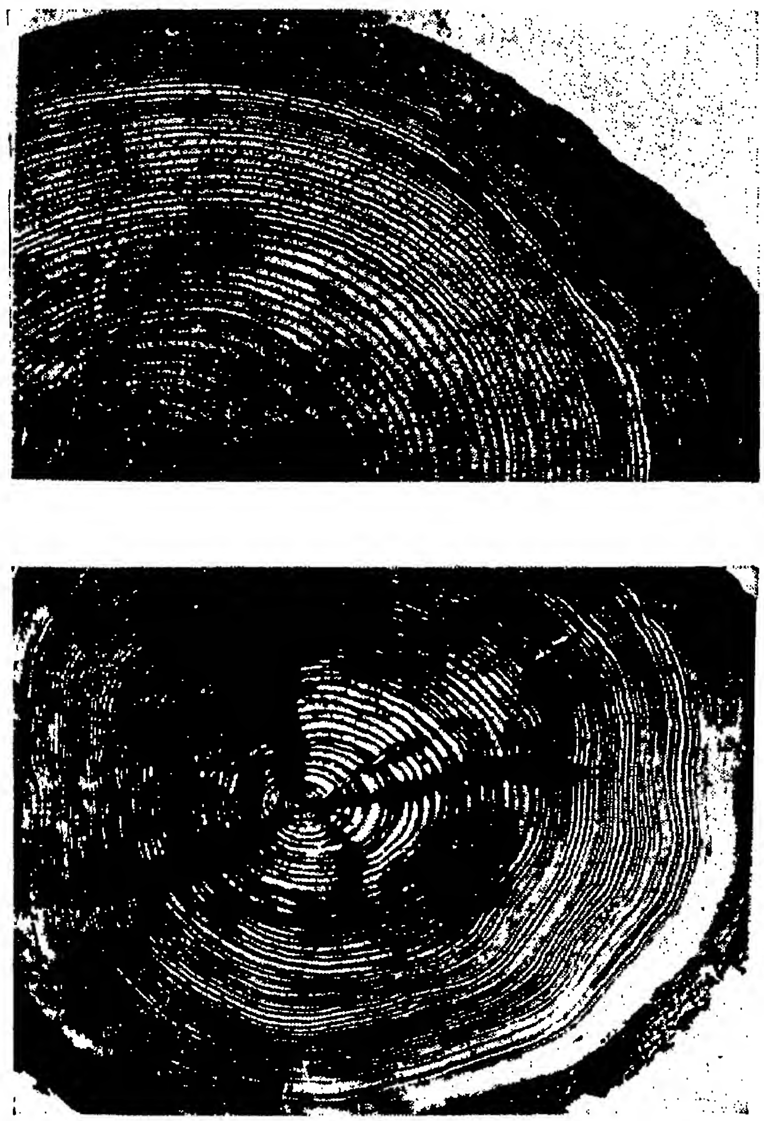

FIG. 157. Sections of coniferous trees, showing a greater annual growth during sunspot maxima.

The distribution of ozone in the terrestrial atmosphere, even if not directly dependent on the variations of solar activity, must nevertheless be correlated to the sun's influence on the earth. It is in fact known that a layer of ozone exists in our atmosphere at a height of about 50 km, and from measurements which are being carried out in various parts of the world it would seem that the presence of this ozone is closely associated with the distribution of atmospheric pressure. Why

this is the case and why the ozone is formed, are problems yet to be solved, but there does not appear to be any relation between the amount of ozone and the disturbances of terrestrial magnetism.

The extensive field of research referred to here, which, as will be understood, necessitates close international collaboration, has as yet hardly been explored at all, and important results are undoubtedly to be expected in the future on this important problem of the sun's influence on our planet, both from the theoretical and from the practical point of view.

The Utilization of Solar Heat

For a long time numerous attempts have been made to utilize the huge amount of energy sent out by the sun to the earth in the form of light and heat, as a means of producing mechanical energy. There are regions on the earth in which the continual action of the sun from a cloudless sky, over an area of about two square metres, may in one day give an amount of energy corresponding to one horse-power. As, however, the rise of temperature produced by directly utilizing solar heat in this manner is comparatively slight, all "sun machines" designed up to the present have too low an efficiency. This explains why such machines have not yet proved a practical success, based as they usually are on the use of large parabolic mirrors which converge the sun's rays at their focus and thus heat water or other substances.

It must also be remembered that, in view of the great abundance of fuels and hydraulic forces nowadays at our disposal and the ease with which they can be put into service, it is probable that all attempts to utilize solar energy in a more or less direct manner will for the moment remain in the experimental stage.

On the other hand, however, it is quite possible that in the more distant future, when fuel reserves begin to give out, it will be found possible to take advantage of the greater facility with which the sun's heat can be used in zones where it is not too much absorbed by condensed water vapour from the atmosphere, and under these conditions solar energy may permit of economical and practical utilization in various forms.

In his youthful years Pacinotti, while inventing his famous "ring," was at the same time a veritable pioneer also in this field of research, as is testified by his writings and discourses on the subject. In a series of letters to his father he explains several plans for the utilization of solar heat, among which was that of making use of the difference in temperature between the surface and the depths of the sea, or of applying the same principle in water reservoirs, as is still being tried at present.

In a lecture given in June 1870 to the Agrarian Society of Bologna he explains other schemes as well, one of which was very promising, it being based on the application of chemical decomposition for driving gas engines, and he closes with the following words: "I cannot present any estimate of the profitableness of these inventions, but I feel justified in the belief that they might be of use in certain favourably situated places. The advantage to be obtained by installing a heat-absorbing apparatus in the Sahara would be very considerable, and if the pipes of the installation were supported by pillars and spaced a good distance apart, they would also protect the region concerned in such a manner as to adapt it for the growth of plants and for human habitation."

In the main the ideas of Pacinotti, as we shall see later, are now beginning to find application, and there is no doubt that definite results will be arrived at. It has in fact been proposed to utilize evaporation basins situated below sea-level, as are to be found in the Lake of Tiberias, the Dead Sea, the Valley of the Jordan, the Caspian Sea or in Eritrea. In the case of the Valley of the Jordan this would be achieved by pumping water from the Mediterranean into a reservoir from which the water would afterwards be discharged by turbines—in two successive stages of about 300 and 200 metres—into the Lake of Tiberias and then into the Dead Sea, with a total power development of 20,000 horse-power, without altering the present hydrologic conditions of that region as a result of the great evaporation. In these schemes the sun's heat would thus only serve the secondary purpose of maintaining the lower basins at a constant or almost constant level.

Winds, too, which owe their origin to solar heat, are being used in various ways for producing mechanical energy, generally on a small scale; more extensive utilization would be

possible, according to modern schemes, by artificially causing solar heat to produce vertically ascending currents of air. The sun-heated air situated at a low level and hence at a comparatively high atmospheric pressure, could, by means of suitable conduits, be made to rise into higher regions of lower pressure. The air passing through the conduits would assume a vortex motion similar to that with which tropical cyclones commence, and, provided the conduits were well protected against radiation, the difference between the temperature of the air emerging from them and the air of the environment should give rise to a current of air having a speed of about 200 km/hour. This current, comparable to that of natural cyclones, would be strong enough to drive turbines installed at the upper end of the conduits. The plants should be built in very hot regions at places where there are steep slopes to sustain the conduits. Favourable conditions for carrying out this scheme would be found in the Sahara, and it appears that efforts in this direction are being made in the Chains of the Atlas and of the Ahaggar, with a view to supplying power to Tunis, Algiers and Morocco.

Another system for indirect solar-heat utilization which has been much discussed of late and has already been put into the experimental stage, consists in producing thermal energy by utilizing the difference in temperature which exists, especially in tropical seas, between water at the surface and water at some depth. The difference of temperature, which for certain seas is calculated to be about 20° C, may produce a water vapour pressure sufficient to work engine-driving machines. After exhaustive preliminary research, experiments were commenced on the island of Cuba, where the temperature of the water and the slope of the sea bottom are particularly favourable for the laying of pipes for conveyance of the hotter water.

The surface water of the sea, having a temperature of 28° C, was sucked up by a pump and made to "boil" by creating a vacuum. The vapour was passed through a low-pressure turbine coupled to a generator and discharged into a condenser which also received the cold water (at about 4° C) from the bottom of the sea, the vapour discharge of the turbine being thereby reduced to water.

The pipe, made of steel plate and measuring more than one

and a half metres in diameter, was laid as low as 600 metres below the surface of the sea. Although the initial results of the experimental plant have not proved very satisfactory, it was calculated that every cubic metre of water brought up from the depths of the sea would, after deducting the power required for driving the auxiliary machinery, furnish a fairly large amount of electrical energy, so that the rather high cost of the installation should be amply repaid.

The use of a liquid with a low boiling point, for instance ammoniac or sulphur anhydride, whose vapours would attain a fairly high pressure to feed the turbine, seems likely to prove advantageous for future experiments on these lines.

The cold of the polar regions has also been thought of as a source of energy, it being proposed to utilize the thermal rise between the water and the air existing in these regions, and there are other plans open to choice, such as the production of electricity from solar radiation by means of the photo-electric effect.

Other very important researches are those on the growth of plants in relation to solar radiation. It is well known that plants grow by absorbing carbonic acid from the air through millions of veins on the back of the leaves. But this absorption takes place only when certain rays contained in sunlight reach the plants, so it may be asked what wavelength the most effective rays possess, what effect is produced by their intensity and by the daily exposure time, by what chemical processes the various parts of the plants are formed, and in what way direct radiation produces movement and causes the plants to bend towards the light-sources. The study of these and kindred problems was commenced a few years ago by the Smithsonian Institution of Washington and other investigators.

The beneficial influence exerted on living organisms by solar rays located at the boundary between violet and ultra-violet and capable of reaching us through the terrestrial atmosphere, is well known in therapeutics, and when, owing to climatic or other conditions, persons under treatment cannot take advantage of these rays from the sun itself, artificial light-sources are used which reproduce the required rays. That solar radiation is necessary and beneficial to the body was known to the ancients, but it can now be stated that,

besides having the visible effect of colouring the skin when directly exposed to the sun, solar radiation acts on certain chemical substances in the skin in such a manner as to make them form vitamin D, which is essential for steady functioning of the human organism. When we receive too small a quantity of solar radiation, there is no opportunity for a uniform quantity of vitamin D to form in the tiny laboratories of our skin, with the result that our organism undergoes general debilitation. Here, again, is a newly-opened field of research which promises important results.

Whilst, therefore, on the one hand the study of solar physics is conducive to greater knowledge of the sun and hence also of the stars, on the other hand the study of geophysics and of the possible applications of solar radiation in the various ways to which we have briefly referred in this work, will increase our knowledge of the sun's influence on the earth and lead to utilization of this immense and bounteous source of energy which we can draw upon so freely, to the greater advantage and well-being of mankind.

REFERENCE LITERATURE

GENERAL TREATISES IN CHRONOLOGICAL ORDER

P. A. Secchi, S. J., *Le Soleil*. Two volumes. Gauthier-Villars, Paris, 1875–77.

Sir N. Lockyer, *Chemistry of the Sun*. Macmillan, London, 1887.

C. A. Young, *The Sun*. Appleton, New York, 1895.

Sir N. Lockyer, *The Sun's Place in Nature*. Macmillan, London, 1897.

Sir N. Lockyer, *Recent and Coming Eclipses*. Macmillan, London, 1900.

E. Pringsheim, *Physik der Sonne*. Teubner, Leipzig, 1910.

J. Bosler, *Les Théories Modernes du Soleil*. Doin, Paris, 1910.

G. Abbot, *The Sun*. Appleton, New York, 1911.

A. Brester Jz., *Le Soleil*. Van Stockum, The Hague, 1924.

Russell, Dugan, Stewart, *Astronomy*. Two volumes. Ginn, Boston, 1926–27.

G. Abetti, *Padre Angelo Secchi*. Agnelli, Milan, 1928.

W. H. Julius, *Zonnephysica*. Noordhoff, Groningen, 1928.

Abetti, Bernheimer, Graff, Kopff, Mitchell. *Handbuch der Astrophysik. Das Sonnensystem*. Springer, Berlin, 1929.

G. Bruhat, *Le Soleil*. Alcan, Paris, 1931.

S. A. Mitchell, *Eclipses of the Sun*. Columbia University Press, fourth edition, New York, 1935.

M. Minnaert, *De Natuurkunde van de Zon*. Van Stockum, The Hague, 1936.

Abetti, Bernheimer, Mitchell. *Handbuch der Astrophysik*. Ergänzungsband. Springer, Berlin, 1936.

Sir F. Dyson and R. v. d. R. Woolley. *Eclipses of the Sun and Moon*. At the Clarendon Press, Oxford, 1937.

INDEX TO SUBJECTS

INDEX TO NAMES